DEPARTMENT OF THE INTERIOR

MONOGRAPHS

OF THE

UNITED STATES GEOLOGICAL SURVEY

VOLUME XLV

WASHINGTON
GOVERNMENT PRINTING OFFICE
1903

UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, Director

THE

VERMILION IRON-BEARING DISTRICT OF MINNESOTA

WITH AN ATLAS

BY

J. MORGAN CLEMENTS

CHARLES RICHARD VAN HISE, Geologist in Charge

WASHINGTON
GOVERNMENT PRINTING OFFICE
1903

CONTENTS.

ILLUSTRATIONS.

ATLAS SHEETS.

LETTER OF TRANSMITTAL.

Department of the Interior,
United States Geological Survey,
Washington, D. C., June 30, 1902.

Sir: I transmit herewith the manuscript, illustrations, and atlas of a monograph on the Vermilion iron-bearing district of Minnesota, by J. Morgan Clements.

This monograph is the fifth one of a series of six which treat of the iron-bearing districts of the Lake Superior region. The monographs on the Penokee, Marquette, Crystal Falls, and Mesabi districts have already been published. The last of the series is a monograph on the Menominee district, by W. S. Bayley. There has also appeared a monograph on the copper-bearing rocks, by R. D. Irving. It is planned to close the work of the United States Geological Survey in the Lake Superior country by a final monograph on the Lake Superior region as a whole.

This report contains the first series of detailed maps of the Vermilion district. This region is one in which the rocks of Archean age contain economic deposits. The geologic mapping of the intricately folded Archean rocks has been a task of very great labor, requiring the full field seasons of several men from 1897 to 1899, inclusive, and a part of that of 1900. The area mapped in detail is about 1,000 square miles.

The topographic work for the report was done by Robert Muldrow and E. C. Bebb, with various assistants. The geologic mapping has been done more largely by J. Morgan Clements than anyone else, but W. S. Bayley and C. K. Leith have also done a large amount of areal mapping, and W. N. Merriam has made a number of large-scale, detailed plats of certain areas having exceptional economic importance. My own part of the work has been a general supervision of the survey. This has involved frequent trips into the district, made in order to assist in solving the general structural problems.

In our work on the Vermilion district we have had the willing help of the officers in charge of the mines, and we are very greatly indebted to them for their assistance. In this connection we would especially mention Mr. D. H. Bacon, who formerly was president of the Minnesota Iron Company, and Mr. T. F. Cole, now president and general manager of the Minnesota Iron Company.

Very respectfully,
C. R. Van Hise,
Geologist in Charge.

Hon. Charles D. Walcott,
Director of United States Geological Survey.

OUTLINE OF MONOGRAPH.

Chapter I. The Vermilion iron-bearing district of Minnesota resembles the other iron-bearing districts of the Lake Superior region in that the rocks are of very great geologic age. Its economic importance has been known for a relatively short time, the first published statement of the occurrence of iron ore in this district having been made in 1850. A brief statement is made of the geologic work previously done in this district, including the names of the geologists by whom it was done, and the scope of the paper is then outlined. The territory included in the Vermilion iron-bearing district lies in the extreme northeastern portion of Minnesota, including portions of St. Louis, Lake, and Cook counties. The district has an area of approximately 1,000 square miles. It is a narrow belt trending east-northeast, which ranges from 2 to 18 miles in width, and has a length of somewhat over 100 miles, extending from the west end of Vermilion Lake to Gunflint Lake, on the international boundary. From a topographic standpoint the Vermilion district is divisible into four areas, each of which is characterized by a fairly distinct type of topographic development. The first of these areas described is the one including the Giants range, the most prominent topographic feature of the Vermilion district. The range reaches an extreme height of 2,120 feet above sea level, but in general is not a very prominent feature throughout its extent. It forms the backbone of the district, extending across it in a northeast direction and dividing it into unequal areas. The second area described lies north of the Giants range and includes all of the areas underlain by the most important iron-bearing formation. This area is characterized by ridges trending N. 70°–80° E., with intervening valleys, the larger ones usually occupied by streams or lakes. In this area the topography is very rugged, but the range in altitude is not great. The third area described is the high plateau country lying southeast of the Giants range and underlain by gabbro. The fourth is a small triangular area at the extreme east end of the district, lying between the Giants range on the north and the gabbro plateau on the south. In this area a rather peculiar topography is developed. The hills have abrupt north escarpments and gentle south slopes. These ridges lie the one south of the other, and present in profile the appearance of a series of saw teeth; hence they are commonly spoken of as "sawtooth mountains." That the drainage system is immature is shown by the abundance of lakes in the district, by the absence of large streams, by the fact that the small and short streams which do exist serve merely to connect the lakes into strings, and by the fact that these streams are frequently interrupted in their courses by rapids and falls. Large swamps still further emphasize this imperfect drainage. The lakes and streams that feed and drain them belong to the large basins of the St. Lawrence River and Hudson Bay. The area belonging to the St. Lawrence drainage basin is very small and is drained by only one small stream, representing the headwaters of the Embarrass River, which flows south and finally empties into Lake Superior. By far the greater part of the district belongs to the Hudson Bay drainage system. All the waters of this system flow north and west, and are collected in Rainy Lake. The streams are short, narrow, and shallow, and form merely the connections between the numerous lakes. The lakes are far more abundant in the eastern than in the western portion of the district. They lie in basins which in general trend east-northeast and constitute the main routes of travel within the district. Most of the lakes have had a mixed mode of origin, owing their existence to pre-Glacial erosion, which scooped out deep valleys, and then to the drift, which left dams across these valleys at intervals along their lengths, forming the strings of lakes that we now find. Other lakes appear to owe their present location and existence solely to glacial action. They are depressions in the drift which have been filled by water. Rock exposures are numerous, especially in the immediate vicinity of the lakes, and are particularly abundant in the eastern part of the district. Only a small area in the district is wooded with old forests. A very large part of the district, particularly the eastern portion, has been burned over repeatedly, and here almost all growth is wanting, or there is but a meager second growth of small timber present. The district is well supplied with fish and game. There are only four towns in the district—Tower, Soudan, Ely, and Winten. Tower is the oldest; it was settled in 1882, and has 1,366 inhabitants, according to the Twelfth Census. Ely, the largest place, has 3,717 inhabitants. The first three places named depend almost altogether upon the mining industry. Winten is a small village whose existence is dependent upon two sawmills which are rapidly cutting the timber remaining in the district. There is one Indian reservation in the district, that of the Bois Fort band of the Chippewa Indians, on Sucker Point, where there are reported to be 808 Indians living. As a matter of fact, there are rarely more than 75 or 100 Indians actually upon the reservation, at least during the summer, the remainder being scattered through the surrounding country. They are not progressive, and while apt in the acquirement of the vices of civilization, do not appear to be willing to bear any of its burdens.

Chapter II. In this chapter there is given a brief statement of the main canoe routes of the district. The methods of travel are described by quotations from the journals of the fur traders, as this shows the conditions existing when the country was being opened up. The methods of travel are now essentially the same, by canoe, although many of the old customs have died out. The remainder of the chapter is devoted to abstracts of articles dealing with the geology of the district. In these abstracts the authors have been quoted very freely. From a perusal of this chapter one can obtain an idea of the growth of knowledge of the geology of the district, which is comparatively difficult of access.

Chapter III. This chapter deals with the Archean.

Section I gives the definition and subdivisions of the Archaen. As a result of studies made largely in this district it was found necessary to modify the definition of the Archean so as to include within it some small quantities of sediments. The Archean of the Vermilion district is divided into three formations, as follows, given from the base up: The Ely greenstone, the iron-bearing Soudan formation, and the granites of Vermilion, Trout, Burntside, Basswood, and Saganaga lakes.

In Section II the Ely greenstone is described. This formation consists of basic to intermediate igneous rocks, and is the lowest member of the geologic column. These greenstones are very widely distributed and occur normally in anticlinal areas, as is shown by the distribution of the overlying sedimentaries. A petrographic study of the greenstones shows that they were originally rocks corresponding in character to intermediate andesites and basic basalts. They have been extremely altered, but retain in many cases in striking perfection the original structures, such as ellipsoidal parting and spherulitic and amygdaloidal structures. A study of their various textures and structures shows that these greenstones are unquestionably of igneous origin, and are largely of volcanic character. With the volcanics there are associated, of course, some intrusives of essentially the same age. These have been subjected not only to the ordinary processes of alteration that have metamorphosed the greenstones, but have been strongly compressed and in many cases have become schistose. Actual green schists, however, are very subordinate in quantity. The greenstones have also been strongly affected by the contact metamorphism due to the intrusion of great granite masses. As a result of this intrusion there have been produced from the greenstones amphibole-schists, which form a marginal facies of the greenstones, lying between them and the adjacent granites. The greenstones have also been metamorphosed by the Duluth gabbro of Keweenawan age, and granular rocks have thus been produced which in most cases show the original textures of the greenstones, but contain also a development of fresh biotite, hypersthene, brown-green hornblende, and magnetite. These greenstones have very slight value at present, although they make good road material.

In Section III the iron-bearing Soudan formation of the Archean is treated. The iron formation is widely distributed in the western part of the district, but is practically wanting in the eastern half. Where it occurs it is found mostly in narrow belts, which consist largely of greenstone so intimately associated with the iron formation that it has been impossible to separate them on the map. In spite of the resistant character of the rocks constituting the formation, exposures are not very good, and it has been difficult to trace out continuous belts. The Soudan being the oldest sedimentary formation in the district has been subjected to all the orogenic movements that have occurred since its deposition. In consequence of this its rocks have been most intricately folded. Where it is exposed most prominently it forms anticlines, although upon these are numerous minor rolls, giving folds with steep pitches. The formation consists of (1) a very subordinate fragmental portion made up of some conglomerate, clearly recognizable as having been derived from the underlying greenstones, grading up into sediments of finer character; and (2) lying above this fragmental portion, the iron-bearing formation proper, which consists of siliceous rocks, largely white cherts—though varying in color from white, green, yellow, and purplish to black—with red jasper and carbonate-bearing chert, grünerite-magnetite-schist, hematite, magnetite, and small quantities of pyrite. These various rocks occur in bands of varying thickness. Where banded they rarely exceed a thickness of 5 or 6 inches. The hematite occurs in certain places in masses of variable size, which constitute the ore deposits. These iron-bearing rocks are clearly of sedimentary origin. They do not now present their original characters, but are presumed to have been derived from rocks that were largely carbonate-bearing, ferruginous cherts. The relation of the iron formation to the adjacent greenstones is clearly that of a sedimentary overlying an igneous series. The few basal conglomerates of the iron formation that have been found consist of pebbles derived from the underlying greenstone, showing conclusively their relationship. This relationship is obscured, however, in most places, by the absence of the conglomerates, and by the fact that the iron formation has been very closely infolded in the greenstone. In consequence of the extreme folding and of the impossibility of determining different horizons in the iron formation, it has been impracticable to ascertain its thickness.

The first published statement of the occurrence of iron ore in the Vermilion district was made by J. G. Norwood in 1850. After a brief period of exploration for gold in the sixties the attention of explorers was turned to the development of the iron deposits. As the result of this development a railroad was built to Tower in 1884, and shipments of the ore began. The ores are extremely hard, massive, blue hematites. In the Chandler mine the ores have been brecciated, but the fragments of the breccia are still the hard blue hematite, averaging about 63.7 per cent iron, 0.05 per cent phosphorus, 4.78 per cent silica, and 5.5 per cent water.

The iron-ore deposits of the Vermilion district show a striking analogy with those of the Marquette district. Like them, they may occur in two positions with respect to the iron-bearing formation. They are found first at the bottom of this formation, and second within it, the ores in both cases being the same in character. The largest known deposits are at Ely. These are typical of the deposits occurring at the base of the formation. They are found at the bottom of a closely compressed syncline of the iron formation which lies in the relatively impervious greenstone. The source of the iron was, in the first instance, the Ely greenstone. From this it was removed through the action of water and collected in the Archean sea to form the sedimentary deposits of the Soudan formation. After the folding of the formation this disseminated iron was carried by downward-percolating waters into places favorable for its accumulation, such as the bottom of this synclinal trough, where it was precipitated by oxygen-bearing waters coming more directly from the surface. Pari passu with this precipitation silica was removed, affording space for the accumulation of the iron to form the ore deposits as now known. The Tower and Soudan deposits differ only in detail from the Ely deposit. They were accumulated in favorable places both at the bottom of the formation, where it rests against the greenstone in which it is infolded, and within the formation in basins formed by the intrusion and subsequent folding of igneous rocks. The mode of accumulation in these is the same as that briefly outlined for the Ely deposits.

The methods of mining in the Vermilion district are briefly described.

In Section IV are described certain acid intrusives varying from fine- to coarse-grained granites, and from porphyries with very fine-grained groundmass to granite-porphyries. The granites are known from the topographic features with which they are associated, as the granites of Vermilion, Trout, Burntside, and Basswood lakes, the granite between Moose Lake and the Kawishiwi River, and the granite of Saganaga Lake. All of these rocks are younger than the Ely greenstone, for they occur in it as dikes. A number of these dikes are found also in the iron-bearing Soudan formation, which is of more recent origin than the greater part of the Ely greenstone. That these intrusives are older than the Ogishke conglomerate (Lower Huronian), which succeeds in age the Soudan formation, is shown conclusively by the fact that pebbles derived from them occur in this conglomerate. The general period of intrusion of all of these acid igneous rocks is placed between the time of the deposition of the latest sediments of the Archean and that of the deposition of the earliest sediments of the Lower Huronian series. Some were perhaps intruded near the beginning of this interval, others probably near the end, but it is now impossible to give their exact ages. In the portion devoted to the granites of the different areas the various intrusives are described somewhat in detail. Their petrographic characters are given as hornblende- and mica-granites, and the various schistose rocks produced from them are described.

Chapter IV. This chapter is devoted to a description of the Lower Huronian series. In Section I are discussed the sedimentary rocks of this series, which have a very large surface extent in the Vermilion district. They are present in two large detached areas, one of which, known as the Vermilion Lake area, extends from the western limit of the area mapped, in the vicinity of Tower, to within about 11 miles of Ely on the east. The second area begins about 7 miles west of Ely and extends eastward to the eastern limit of the area mapped. This is known as the Knife Lake area. The rocks of these two areas, although of slightly different petrographic character, are of essentially the same age. At the base of the series there lies a great conglomerate, known as the Ogishke conglomerate. The relation of this conglomerate to the formations previously described is conclusively shown by the fact that it consists of pebbles and finer detritus derived from the Ely greenstone, the Soudan formation, and the various acid intrusives already mentioned. Above this conglomerate in the eastern portion of the district there are found in a few localities small masses of the iron-bearing Agawa formation. This formation is petrographically the same as the Soudan formation. In it, however, there is in places a development of the carbonate-bearing facies. No iron ores have been found in it, and it is of so small a surficial extent, and so thin, that no large iron-ore deposits will probably ever be found in it in the United States in the Vermilion district proper. A reconnaissance made in the adjacent portion of Ontario indicates that it is there better developed than on the United States side of the border, and it may possibly contain iron deposits in this area, although this does not seem to be very probable. This iron-bearing formation is wanting in the western portion of the Vermilion district.

Overlying the Ogishke conglomerate in the western portion of the district and the intervening iron-bearing Agawa formation where present in the eastern portion of the district, there occurs a thick series of slates of varying character, to which the name Knife Lake slates has been given. These slates have been very closely folded. Owing to the lack of well-defined horizons in the conglomerates and in the slates it has been impossible to trace out the structure of this series by following key rocks. The folding has, however, been proved in many localities by a study of the distribution of these rocks. The relation of this series to the older rocks is shown by the fact that it consists of detritus derived from these older rocks. In three large areas granites which are younger than the sediments are associated with them. These granites are known as the Giants Range granite, the Snowbank granite, and the Cacaquabic granite. This relationship is proved by the fact that these granites cut through, send offshoots into, and have metamorphosed the sediments. As a result of this metamorphism, micaceous conglomerates in which the conglomeratic structure is still recognizable have been produced from the Ogishke conglomerate, and mica-schists have been produced from the Knife Lake slates. These sediments are also metamorphosed by the Duluth gabbro, which has changed them into mica-schists. Hence the gabbro is younger than the sediments. In addition there are found in the rocks of the series certain basic dikes which are similar to others which cut the Duluth gabbro, and which are considered to be of Keweenawan age.

In Section II of this chapter various acid intrusives of the same general character petrographically, and of the same geologic age, are discussed. They are granites and granite-porphyries which occur in large masses and in dikes penetrating the surrounding Lower Huronian sediments and other adjacent rocks. From their occurrence in the vicinity of the Giants Range, Snowbank Lake, and Cacaquabic Lake these names have been given to the granites occurring in these areas, respectively. There is included also a description of some acid and intermediate intrusives of the same age as the large masses of acid intrusives. The Giants Range granite is a hornblende-mica-granite, and varies from very fine-grained rocks through medium-grained to coarse-grained rocks. The Snowbank granite also varies from fine- to coarse-grained forms, with medium-grained facies as the most abundant type. Certain porphyritic facies of the granite also occur. This granite varies from a normal mica- and hornblende-granite to an augite-granite, and by loss of quartz to a syenite. The Cacaquabic granite is somewhat more interesting than the preceding ones, in that it is one of the rather exceptional augite-soda-granites. The main mass of this granite is developed as a medium-grained gray or pink to red granite, whereas on the periphery of the granite area a finer-grained granite and also a granite-porphyry facies of the rock are developed. In addition to this there are various granite and granite-porphyry dikes whose immediate relationship to the granite massives already described could not be traced in the field. A section is devoted to a brief description of certain basic and intermediate intrusives of doleritic and lamprophyric character, which bear the same relations to the various adjacent formations as do the acid rocks previously described.

Chapter V. This chapter treats of the Upper Huronian (Animikie) series. This series is found in the extreme eastern portion of the district, where it underlies a relatively small area. It is known, however, to have enormous development to the east, immediately beyond the limits of the Vermilion district, and also to the south-southwest, in the adjacent Mesabi district. This Upper Huronian series may be readily divided into two facies of rocks that are quite different petrographically. At the bottom of the series occurs an iron-bearing formation known as the Gunflint formation. Above this occurs a great slate-graywacke formation to which the name Rove slate has been given. The Gunflint formation is correlated with the Biwabik formation of the Mesabi district. It has a very limited development in the Vermilion district, and its most interesting phases are especially well developed in the vicinity of Akeley Lake. In general the rocks of this formation have a monoclinal dip to the south-southeast at a low angle, but variations in the strike and dip indicate clearly that the structure is not so simple as it appears to be. Minor folds have been traced. Petrographically the rocks of the Gunflint formation are peculiar. Where least metamorphosed, they consist of thin bands of nearly pure chert alternating with cherty and granular quartzose bands containing varying percentages of iron carbonate, bands of jasper, magnetitic chert, and other bands consisting of quartz as a basis with actinolite and grünerite crystals. With these minerals are always associated more or less ferruginous carbonate, magnetite, hematite, and limonite. In these rocks we find developed the peculiar oval, crescent-shaped, and rounded granules which are so characteristic of the Biwabik formation of the Mesabi range—granules made up in their freshest condition of a hydrous ferrous silicate of varying shades of green. These rocks have been extremely metamorphosed by the Duluth gabbro. Where most metamorphosed the iron-bearing Gunflint rocks are composed of coarsely crystalline bands of quartz, of varying width, alternating with coarsely crystalline bands of magnetite ore reported to vary from 1 inch up to 10 or 12 feet in thickness, and of bands of dark-green, brown, or black rocks that consist of combinations of quartz, augite, hypersthene, hornblende, olivine, and magnetite as the principal minerals, but associated occasionally with some ferruginous carbonate, actinolite, and grünerite. The rounded granules are sometimes preserved in these rocks, showing their derivation from the least metamorphosed forms previously mentioned, although the granules consist of minerals different from those in the least metamorphosed forms. The Rove slate conformably overlies the Gunflint formation. The rocks of this series show nothing of especial interest. They have been metamorphosed slightly as a result of the contact action of the adjacent Duluth gabbro mass and the intrusive Logan sills.

Chapter VI. This chapter treats of the Keweenawan series. The only rocks of this age in the Vermilion district are gabbros forming a part of the Duluth gabbro mass of northeastern Minnesota, certain great basic sills to which the name Logan sills has been given, and some few basic and acid dikes which cut all the rocks of the district, including the aforementioned Duluth gabbro and the Logan sills. The studies of the writer and his associates have been confined chiefly to the northern edge of the Duluth gabbro, which appears in the Vermilion district. Several reconnaissance trips have also been made into the area underlain by the gabbro. As a result of these studies, the Duluth gabbro is found to vary in texture from a coarse-grained granular rock to a relatively fine-grained rock. It also has in places a gneissic structure. Under the microscope the texture is seen to vary from granular to ophitic. The Logan sills are great masses of doleritic rocks that occur for the most part as sills interbanded with the Upper Huronian sediments, and at times cut in dike form across them. Petrographically these dolerites range from coarse-grained rocks, found in the centers of the sills, with an imperfect granular texture and very similar to the gabbro, through normal ophitic dolerites, to intersertal textured basalts on the selvages of the sills. The gabbro is found to metamorphose all of the sediments already enumerated, and is thus shown to be one of the youngest rocks of the district. It is also found to be intrusive in the Keweenawan volcanics. A number of facts are enumerated to show that the gabbro and the Logan sills are of essentially the same petrographic character, although they exhibit minor differences that are readily explicable when one considers the relative amounts of the two rocks. After a consideration of these facts and of the stratigraphic relationship of the rocks the conclusion is reached that the gabbro and the sills are of essentially the same composition and age, having been derived from the same parent mass of magma. In certain localities in the Duluth gabbro there are found masses of titaniferous magnetite of varying size, with some associated minerals. These masses grade into the surrounding gabbro, and were formed as the result of processes of segregation. No published description has yet been given, so far as the writer knows, of any large continuous masses of titaniferous magnetite in these gabbros, and he knows of none from personal observation. If, however, large masses do exist their content of titanium would prevent them from being of value at the present time, when, according to the modern iron-smelting practice, titaniferous ores can not be smelted economically. In a short section mention is made of the acid dikes that are younger than the Duluth gabbro, and of certain basalt and dolerite dikes that are younger than the gabbro and that cut the acid dikes, which themselves cut the gabbro.

CHAPTER VII. In this chapter the drift is briefly described, the general distribution of the Vermilion moraine is outlined, and the locations of certain glacial lakes are stated.

CHAPTER VIII. This chapter consists of a brief discussion of the topography of the district in its relation to the geologic structure.

CHAPTER IX. This chapter is devoted to a discussion of the general geologic history of the district as determined by the various facts set forth in previous chapters.

THE VERMILION IRON-BEARING DISTRICT OF MINNESOTA.

By J. Morgan Clements.

CHAPTER I.

GENERAL DESCRIPTION OF THE DISTRICT.

INTRODUCTION.

The Vermilion iron-bearing district of Minnesota is like all of the other iron-bearing districts of the Lake Superior region in that the rocks are of very great geologic age. Its economic importance has been known, however, for a comparatively short period. The first statement of the existence of iron ore in this district is credited to J. G. Norwood, who observed it upon his explorations in 1850 and refers to it in his report.[a] It was not until the early eighties that a determined effort was made to develop the iron resources which some then knew were in this district. In 1884 the railroad from Duluth was completed to Tower, and the first shipment of iron ore was made. From this time on the development of the iron resources of the district was rapid, as is shown by the annual increase in the shipments of ore. This increase, with minor fluctuations in 1893 and 1898, caused by financial conditions, continued up to the season of 1902, when the maximum shipment for the district, 2,083,784 tons, was reached.

PREVIOUS GEOLOGIC WORK IN THE DISTRICT.

Mr. Bailey Willis, special agent of the Census Office of the United States, spent one month, October 10 to November 10, 1880, studying the

[a] Report of a geological survey of Wisconsin, Iowa, and Minnesota, by D. D. Owen, 1852, report of J. G. Norwood, p. 417.

geology of the part of the Vermilion district in the immediate vicinity of Tower. In 1883–1885 Prof. R. D. Irving spent several months studying the geology of this district. He was assisted in 1883 by Mr. W. M. Chauvenet and in 1884 by Mr. W. M. Chauvenet and Mr. W. N. Merriam. These studies were continued in 1885 and 1886 by Mr. W. N. Merriam, assisted in 1886 by Mr. W. S. Bayley during a portion of the season. In 1888 Prof. C. R. Van Hise visited the district, traversing it from end to end. The general results of these trips, which were made for the United States Geological Survey, were embodied in various papers which are referred to under the review of the literature (Chapter II of this monograph) and in manuscript reports that are preserved in the office of the Survey. Various members of the Minnesota Geological Survey have spent parts of or entire field seasons in the district, and their results are published in the reports of the State survey.

In pursuance of a plan to study each of the Lake Superior iron-bearing districts and make detail reports on them the United States Geological Survey resumed work in the Vermilion district in 1897. This work has been under the general charge of Prof. C. R. Van Hise. The geologists in the field were Messrs. W. S. Bayley, C. K. Leith, and J. Morgan Clements. The field work continued through the field seasons of 1897, 1898, 1899, and 1900. Professor Van Hise was in the district for short periods during the different seasons, and in 1899 he spent a large part of the season in active field work. Mr. Bayley spent the seasons of 1897 and 1898 in the field; Mr. Leith spent the seasons of 1897, 1898, and 1899; and Mr. Clements (the writer) was present every year, remaining throughout the entire season.

In preparing this report the writer has, of course, made use of the material obtained by the other members of the survey, and is very greatly indebted to them for the assistance given by their carefully prepared notes. He is, however, chiefly under obligations to Professor Van Hise, who, in the first place, gave him the opportunity to prepare the report, and who has ever been ready to assist him both in the field and in the office.

The mining men of the Vermilion district have, almost without exception, shown high appreciation of the work done in other districts by the United States Geological Survey, and have rendered all legitimate assistance within their power during the progress of the work. The Minnesota Iron Company, under the presidency of Mr. D. H. Bacon, and later of Mr. T. F.

Cole, gave invaluable aid. In 1899 the company began a careful geologic survey of its lands, which was made in far greater detail than was possible by the United States Geological Survey under existing conditions. This private survey was carried out by Mr. W. N. Merriam, assisted in 1900 by Mr. Oscar Rohn All of the material resulting from this survey has been placed at the disposal of the writer and his collaborators; a great deal has been used in compiling the maps published herewith, and it has added very materially to their completeness. Moreover, Mr. Merriam has taken pains to make drawings, some of which are reproduced in this report (credited to him), and otherwise to render assistance. To the company which he represents, and to him especially, the United States geologists are deeply indebted. The writer wishes also to acknowledge here the great assistance rendered by Mr. E. R. Maurer and Mr. C. F. Graff, who have prepared the drawings from which the maps and plates are made, and by Mr. F. B. Van Horn, his efficient stenographer.

SCOPE OF THE PAPER.

The attempt has been made to make this report a complete epitome of our knowledge of the Vermilion district. At the same time many details have necessarily been omitted, although in most cases these concern the formations of the district that are not of economic value and are not likely to become important. These details, without adding to the general results, would have very much increased the bulk of the volume. Moreover, it was feared that they would obscure important facts and thus defeat the object of the monograph.

The report is intended primarily to give to mining men and to present and prospective owners of property in the district information concerning the distribution of the important iron-bearing formations and their relations to the other rocks associated with them. The text gives a full description of these formations.

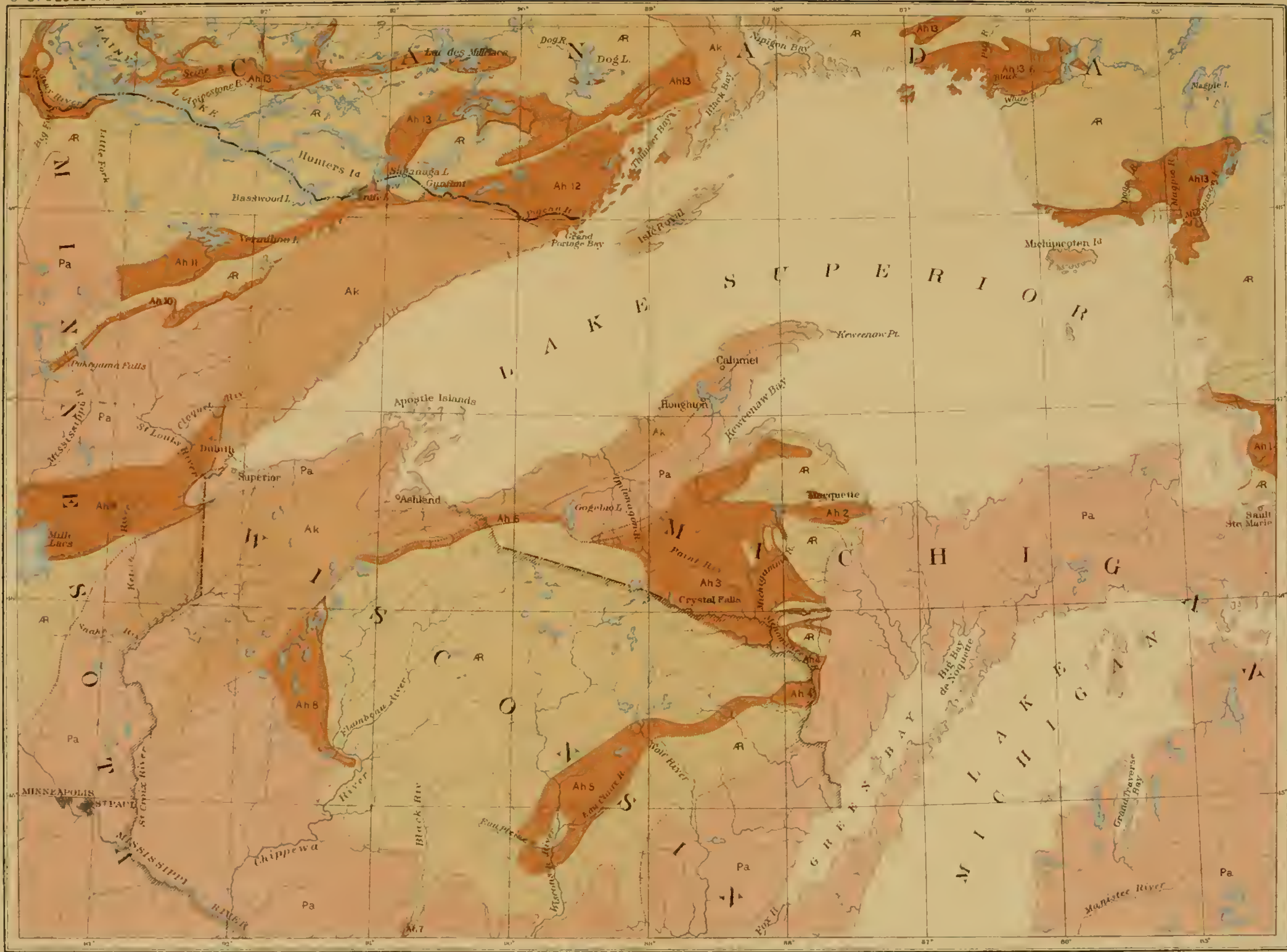
The atlas of maps and the plates in the volume are for the purpose of aiding in an understanding of the textual descriptions. Actually observed exposures of the rocks of the district could not be indicated in all cases on the maps because their scale is too small. Large-scaled maps of certain portions of the district that contain the important iron-bearing formation in its best development, and in which areas any industrial developments of the future are likely to occur, have been prepared. On these plates the exposures actually seen during the field work have been indicated, drawn to very nearly correct scale. Many of the exposures are so small that in order to represent them on the maps at all it has been necessary to exaggerate them. On these maps are given the data which were used as the basis for drawing the formation lines in these economically important areas. If anyone is unable to accept the conclusions reached, he may draw his own inferences from the data given, which are essentially correct, although, as will be understood by those who know the limitations under which such geologic mapping is done, a number of minor errors may be disclosed by very close work and very exact location of exposures with instruments of precision. All geologic maps are but approximations to the truth. The aim has been to make the present approximation as close as practicable.

A great deal of time has been devoted to examining all available literature that refers in any way to this district. Fairly complete quotations are made from the various works cited, so that a careful reading of the review of the literature will enable one to familiarize himself with the changes of opinions concerning the structure, character of rocks, and other details, and also with the gradual increase in knowledge concerning the geology of the district.

GEOGRAPHIC LIMITS.

The territory designated by the name "Vermilion iron-bearing district" lies in the extreme northeastern portion of Minnesota, including portions of St. Louis, Lake, and Cook counties. The district has an area of approximately 1,000 square miles. It is a narrow belt extending east-northeast from near the west end of Vermilion Lake, in longitude 92° 30′ west from Greenwich, on the west, to the vicinity of Gunflint Lake, on the international boundary, on the east, in about longitude 90° 45′ west from Greenwich. The district lies between 47° 15′ and 48° 15′ north latitude. It attains its maximum width at the west, where it is about 18 miles wide, and gradually narrows eastward, until at Gunflint Lake its minimum width is 2 miles. The geographic relations of the Vermilion iron-bearing district of Minnesota to the other iron-bearing districts of the Lake Superior region can be seen on Pl. I.

The western limit of the district as given on the map (92° 30′) is purely arbitrary. West of this the country is heavily drift covered and timbered, and



ALGONKIAN

ARCHEAN	HURONIAN	KEWEENAWAN	POST ALGONKIAN
Æ	Ah	Ak	Pa
Including considerable areas of Algonkian granite	Including considerable areas of Archean (the iron-bearing series)		

HURONIAN

- Ah 1 *Original Huronian*
- Ah 2 *Marquette series (iron-bearing)*
- Ah 3 *Crystal Falls series (iron-bearing)*
- Ah 4 *Menominee series (iron-bearing)*
- Ah 5 *Wisconsin Valley series*
- Ah 6 *Penokee-Gogebic series (iron-bearing)*
- Ah 7 *Black River schists (iron-bearing)*
- Ah 8 *Chippewa Valley quartzites*
- Ah 9 *St Louis series*
- Ah 10 *Mesabi series (iron-bearing)*
- Ah 11 *Vermilion series (iron-bearing)*
- Ah 12 *Animikie series (iron-bearing)*
- Ah 13 *Folded schists of Canada*

GEOLOGIC MAP OF PART OF THE LAKE SUPERIOR REGION

SHOWING PRE-CAMBRIAN ROCKS

Compiled from official maps of United States, State, and Canadian surveys

Scale

0 50 100 statute miles

great muskegs[a] extend over large areas. In that region outcrops are very scarce, but exposures of banded jasper and iron ore have been found associated with greenstones, granite, and clastic sediments. A reconnaissance trip was made through it in 1886 by Mr. W. N. Merriam for the United States Geological Survey, and this work, as well as that done in that portion of the district for private corporations, to whose results the Survey has had access, shows the futility of attempting at present to trace out formation lines in that region. Hence the Survey has done no detailed work west of the above line.

The same rocks that occur at the eastern end of the district are known to continue for many miles eastward, both in the United States and in Canada. Hence this eastern limit also is arbitrary, and includes, indeed, rocks that are the direct eastward continuation of the topographic feature known as the Mesabi range, which in the western part of the district lies south of the Vermilion.

The southern and northern limits are sharply defined, and are well marked geologically by granite and gabbro. The gabbro bounds only the southern side of the district in the eastern part.

STRATIGRAPHY.

The stratigraphic succession in the Vermilion district is as follows, in descending order:

Pleistocene	Drift.
Keweenawan	Duluth gabbro and Logan sills.
(Unconformity.)	
Upper Huronian (Animikie series). Confined to east end of district	Rove slate. Gunflint formation (iron-bearing).
(Unconformity.)	
Lower Huronian	Intrusives. Granites, granite-porphyries, dolerites, and lamprophyres. Knife Lake slates. Agawa formation (iron-bearing). Ogishke conglomerate.
(Unconformity.)	
Archean	Intrusive granites, granite-porphyries, and some greenstones. Soudan formation (the iron-bearing formation). (Minor unconformity.) Ely greenstone, an ellipsoidally parted basic igneous and largely volcanic rock.

[a] These muskegs, as they are called by the Indians, are great open swamps that are comparable in a way with the northern tundras. They have been formed in most cases by the drying up of large bodies of water, and in many of them there is now an open area occupied by the remnant of a larger lake. Over the area surrounding the water there is spread a growth made up largely of sphagnum moss, wild cranberry bnshes, and other water-loving plants, with occasional swamp-growth shrubs that attain a height of 1 to 3 feet. Ont of this thick undergrowth there rise isolated tamarack and spruce trees, usually of small size. Where these muskeg swamps border the large lakes they are sometimes flooded during high water.

The evidence upon which the above formations are grouped into series and these correlated with the formations in other districts of the Lake Superior region will appear in subsequent pages. In this place is given merely a categorical statement of the problems to be treated.

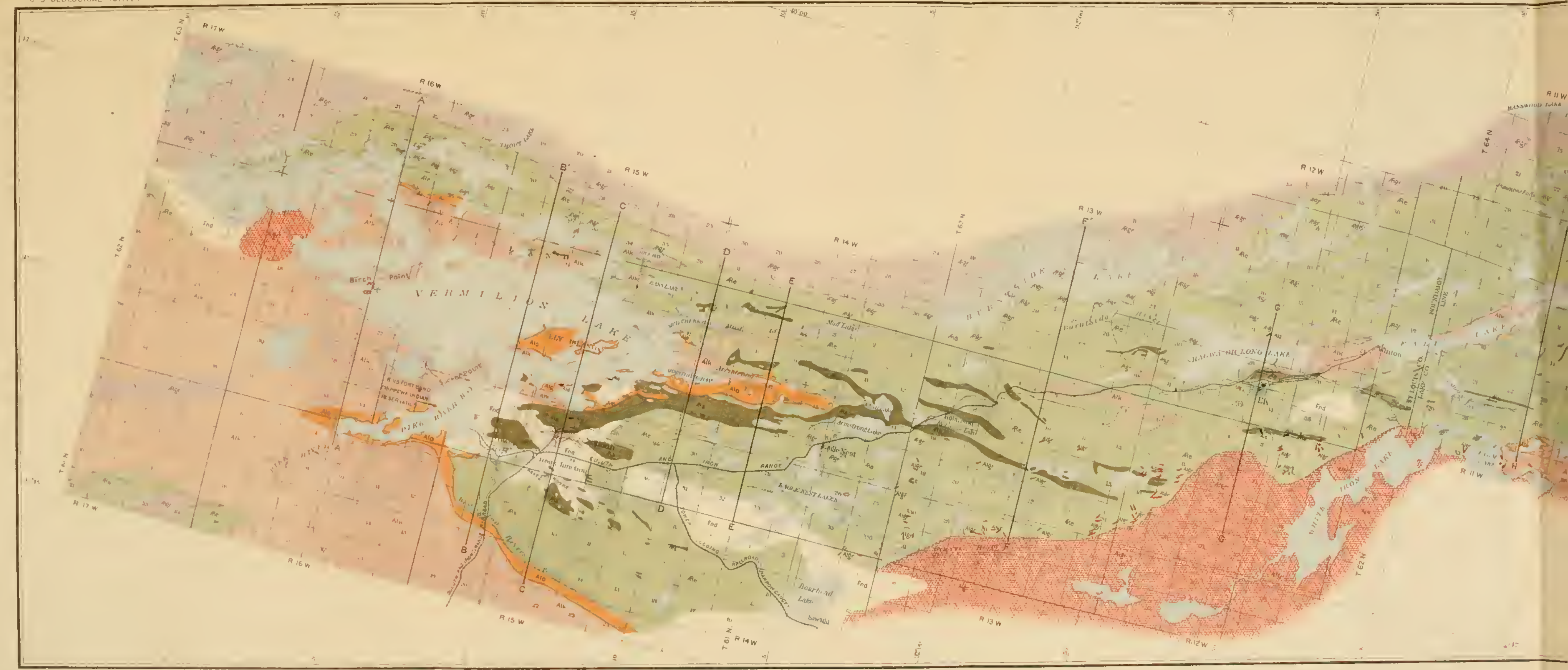
The accompanying general map (Pl. II) shows the distribution of the various formations enumerated above. The reader is able to get a better idea of the relationship of the formations and their distribution throughout the entire district from a study of this general map than he could from the examination of the larger-scale maps in the atlas, which are of relatively small areas. On the larger-scale sheets, in the accompanying atlas, details of topography are shown which could not be shown on the general map. These atlas sheets and the other more detailed sheets on a still larger scale are more accurate than the general map and should be used in a detailed geologic study of the district having in view the location of possible productive properties.

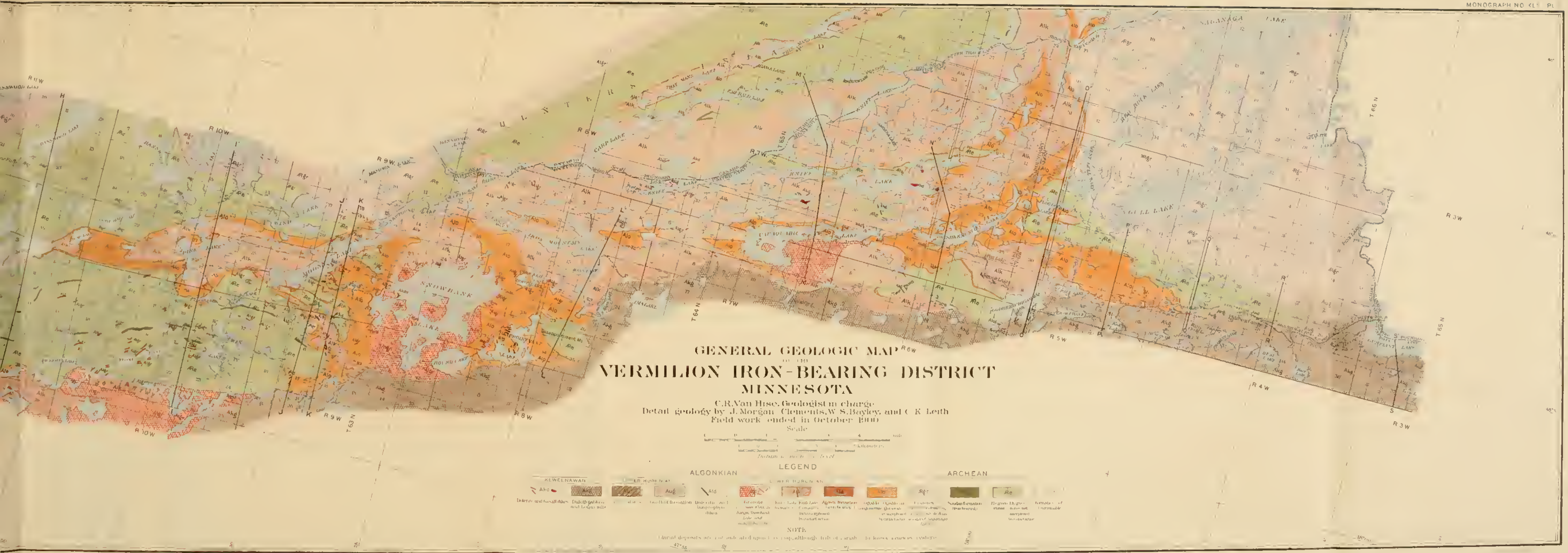
PHYSIOGRAPHY.

RELIEF.

That portion of Minnesota included within the limits given above is most commonly known in commercial reports and locally as the "Vermilion iron range." The term "range" is in this case, however, a misnomer, if one understands thereby an area with strongly marked topographic features which cause it to stand out from the adjacent areas. The Vermilion district is one in which the relief is not very great. The maximum elevation is attained by a hill in sec. 28, T. 65 N., R. 4 W., near the east end of the district, which reaches a height of 2,120 feet above sea level, or 1,518 feet above the mean level of Lake Superior, which is 601.56 feet above the sea. This is one of the highest points in the State, the highest hill having a reported altitude of 2,230 feet.[a] The lowest valley is that occupied by Basswood Lake, in which the water level is 1,300 feet above the sea, or 698 feet above Lake Superior. There is, then, a difference of 820 feet between the lowest water level and the highest hill within the district. The above extremes in height are found at opposite ends of the district, and, as the general slope is to the northwest, the average relief is very much less than 820 feet, approaching 400 or 500 feet. It is to be further

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 481.


VERMILION LAKE
Birch Point
PIKE RIVER BAY
PIKE RIVER
Armstrong Lake
Eagle Nest
Burntside
BURNTSIDE LAKE
SHAGAWA OR LONG LAKE
Ely
Winton
WHITE IRON LAKE
Bearhead Lake
R 17 W
R 16 W
R 15 W
R 14 W
R 13 W
R 12 W
R 11 W
T 63 N
T 62 N
T 61 N
T 64 N
ST LOUIS CO
LAKE CO



C.R. Van Hise, Geologist in charge
Detail geology by J. Morgan Clements, W. S. Bayley, and C. K. Leith
Field work ended in October 1900

noted that in general the changes in relief are very rapid, and as a consequence the district is extremely rugged in detail, diversified by hills and many lakes, with an occasional muskeg. Over the greater portion of the area we find east-northeast trending ridges alternating with valleys occupied by long lakes, or chains of lakes, or streams. As a consequence, in traversing the district from north to south one is continually ascending a steep ridge to descend on the opposite side into a valley which is usually occupied by a lake.

The Vermilion district, considered broadly, may be divided into four areas, each of which is characterized by a fairly distinct kind of topographic development. These are:

(1) The area including the Giants range, which is the most prominent topographic feature of the Vermilion district.

(2) A broad area north and northwest of the Giants range, including all the areas underlain by the iron-bearing formation. This is very rugged, but the differences in altitude are not great.

(3) An area of high plateau country southeast of the Giants range, underlain by gabbro.

(4) A small triangular area at the extreme eastern end of the district. The apex of the triangle is toward the west, and lies between the Giants range on the north and the high plateau to the south.

Mesabi or Giants range.—This is a fairly well-marked east-northeast trending range of hills,[a] which runs obliquely across the district. It forms the backbone of the Vermilion district, although it is unsymmetrical and divides the district into unequal areas. It enters the district in T. 62 N., R. 12 W., and extends in an east-northeast direction along the Kawishiwi River, south of Snowbank Lake and Cacaquabic Lake, and north of Lake Gobbemichigamma to the east side of T. 65 N., R. 4 W., where it leaves the district and enters Canadian territory.[b] The maximum height of this range is attained by a hill in sec. 28, T. 65 N., R. 4 W., already

[a] This range has been known as the Mesabi for an unknown length of time by the Indians inhabiting this region, and has been so called in the reports of Western explorers or else translated by them into Giants range. In late reports Prof. N. H. Winchell has applied the term Mesabi to a range of hills lying south of that known as the Giants range proper, to which the above statements apply. Winchell has his Mesabi and Giants range proper unite a short distance southwest of Birch Lake and form the Giants range to the east. West of this point he discriminates the range into the Giants range to the north and the Mesabi to the south. Geol. and Nat. Hist. Survey of Minnesota, Thirteenth Ann. Rept., 1885, p. 22; Final Rept., Vol. IV, 1899, p. 232.

[b] N. H. Winchell, Geol. and Nat. Hist. Survey of Minnesota, Thirteenth Ann. Rept., 1885, p. 38.

referred to as the highest hill in the district, which reaches 2,120 feet above sea level. This is about 460 feet above the general level of the surrounding country. As a general thing the range does not stand out very prominently from the rest of the district. Between Gobbemichigamma and Cacaquabic lakes, however, there is a subordinate range, with Twin Peaks as the highest points, which forms a very prominent feature of this part of the district. The Giants range is not continuous throughout. It is made up of a great number of small hill ranges having in general the trend of the main range to which they belong. Its contours are commonly smooth and rounded, as the result of glaciation. On its slopes are many minor irregularities caused by glacial deposits. Among these deposits we find now small glacial lakes almost upon the summit of the range.

Area north and northwest of Giants range.—It has been said that the Giants range divides the Vermilion district topographically. The area with the largest surface extent is that lying north and northwest of the range. This area merges to the south into the Giants range, and continues to the north beyond the limits of the area mapped. Within this area the topography is that which has been briefly described on p. 35 as fairly typical for the entire district. It consists in ridges trending N. 60°–80° E., and separated by valleys which are usually occupied by a long lake, a string of small lakes, or a stream. The ridges are usually about 200 feet above the lakes. The greatest height in this portion of the district is reached by Chester[a] or Jasper Peak, in sec. 35, T. 62 N., R. 15 W., which is 1,710 feet above sea level. The topography is less rugged in the western part of the district, where the hills and ridges have been apparently more affected by glaciation. They are there generally rounded and the slopes are much gentler than in the eastern portion. In the east the area is underlain by a great slate formation, and the jointing of the slates has caused the development of minor drainage lines and ridges transverse to

[a] The name Chester was the first recorded name given to this peak by white men. It was so called in honor of Prof. A. H. Chester, who did the first important work toward exploiting the iron deposits of this district. The peak is the most prominent topographic feature of this part of the district. It is an almost bare knob of jasper. This jasper is one of the important rocks of the Lake Superior iron region, and as everyone is more or less familiar with it, the peak has naturally been called after the rock of which it is formed. The writer thinks that it will be impossible to cause the name Chester to be generally used, although by priority this name rightfully should be given to the peak.

the trend of the other topographic features. Moreover, the slates break off, forming steep cliffs that surround the ridges and hills, instead of the moderate slopes more common in the western part of the district. The valleys are almost flat and are exceptionally wide. In short, the wide U-shaped form is the common one here, rather than the flaring V-shaped valley characteristic of rivers. The modification of the topography from the V-shaped to the U-shaped forms is attributed to glacial erosion and deposition.

One area in which rather interesting topography was observed is that extending from about 1½ miles southeast of Ely, in sec. 2, T. 62 N., R. 12 W., southwestward to sec. 30, T. 62 N., R. 12 W., including about 14 square miles. This area is underlain by the Giants Range granite, and throughout the relief is very slight, the greater portion of the land surface being only a foot or so above the level of the lakes. As a result the major portion of it is a marsh. The knolls are of granite, with low, rounded surfaces rising only a few feet above the swamp area. A few of the knolls are composed of glacial drift. Evidently pre-Glacial drainage had been especially vigorous here, and this is a small, nearly base-leveled area, with the lakes as the base-level.

On a reconnaissance trip along the international border a similar area was noted surrounding the southeast side of Iron Lake, in secs. 11 and 12, T. 66 N., R. 13 W., and sec. 7, T. 66 N., R. 12 W., outside of the Vermilion district. Here base-leveling has proceeded farther than in the area previously mentioned; the islands in this portion of the lake rise just above the water level, and the small streams entering the lake here flow with meandering courses through wide marshes.

The gabbro plateau.—In northeastern Minnesota, southeast of the Vermilion district proper, there is a large area underlain by gabbro. Only a small portion of this area comes within the region shown on the accompanying general map, and that portion is a strip on its southern and southeastern edge. Knowledge of the plateau has been derived from a study of this strip, where for the most part stratigraphic work ended; from the results of a reconnaissance trip within the area underlain by the gabbro; and chiefly from the description by Dr. U. S. Grant in the last Minnesota report,[a] to which the reader is referred for greater detail. Dr.

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, pp. 434–436.

Grant describes the gabbro area as an elevated plateau, upon whose surface, however, there are many minor irregularities, but few of which rise 100 feet above the surrounding country. Lakes are common, but very shallow. "The general plain-like character of the gabbro-covered area can be ascribed to weathering, erosion, and glaciation acting on a surface composed of a single rock mass (the gabbro) uniform in constitution, grain, and resistance to disintegrating agents."[a]

Gunflint Lake area.—Near the east end of the district, as shown on the map (Pl. II), there is an area having approximately the shape of an isosceles triangle, with the apex of the triangle pointing west. The north side is bounded by the Giants range, the south side by the gabbro plateau, and the base is the eastern limit of the region shown on the general map. Within this area a very interesting kind of topography is developed. The following description is based upon a personal visit to the greater portion of the area described, and upon the published reports of Dr. U. S. Grant.[b]

This area is underlain by a series of Upper Huronian slates which have a low dip to the south-southeast. The continuity of the slate series is interrupted by numerous sills of coarse dolerite of varying thickness, which were intruded approximately parallel to the beds. Pre-Glacial erosion developed here a system of east-west ridges and valleys. Each ridge is capped by a layer of dolerite and below, protected by this hard upper layer, lie the slates. The ridges slope gently to the south. The slope follows approximately the upper side of the dolerite sill and corresponds closely to the dip of the sediments. To the north the ridges break off abruptly, giving a steep or precipitous escarpment with a talus below. The narrow valleys between the ridges are usually occupied by lakes, and each lake is higher than the one in the valley next north of it. A cross section would show on the north a talus surmounted by a cliff which forms the brow of the ridge, the latter sloping gently to the south to the valley, which contains a lake. Then the talus, cliff, and slope are repeated. Such a north-south section would have much the jagged appearance of the edge of a saw. From this character these hills are frequently spoken of as the "sawtooth hills."

---

[a] Grant, op. cit., p. 435.

[b] Op. cit., pp. 317, 482.

The entire district has been overrun by glaciers, and in consequence glacial drift is widely distributed. In places it is very thin, but in other places it has accumulated to a considerable depth over large areas. In these areas the striking features of the topography are due essentially to the drift. However, the present relief can easily be seen to have been superimposed upon a pre-Glacial topography of very different character. A deep covering of drift occurs in all four of the greater areas above outlined, and modifies the topography locally.

DRAINAGE.

One can not glance at the topographic maps of the Vermilion district in the accompanying atlas without being impressed by the abundance of lakes in it. These numerous lakes, with their connecting streams, make the district comparatively easy of access. They have enabled us to study the geology with a much smaller expenditure of time and money than would be required if they did not exist. The presence of these lakes is clearly indicative of an immature drainage system, which is further shown by the absence of streams of large size, by the fact that the small and short streams which do exist merely serve to connect the lakes into strings, and, by the fact that these streams are frequently interrupted in their courses by rapids and falls. The presence of large muskegs in some portions of the district still further emphasizes this very imperfect drainage.

Hydrographic basins.—These lakes and the streams which feed and drain them belong to the large hydrographic basins of the St. Lawrence River and Hudson Bay. The area belonging to the St. Lawrence drainage basin is very small. It is drained by a small stream—the headwaters of the Embarrass River, a tributary of the St. Louis—which rises in Putman Lake, sec. 18, T. 61 N., R. 14 W., and flows south, finally emptying into Lake Superior. It is interesting to note that this small stream, flowing south, runs for a considerable distance, in the area outside of the district mapped, nearly parallel with Pike River, a stream 5 miles west of it, whose waters flow north and belong to the Hudson Bay drainage.

By far the greater part of the district belongs to the drainage basin of Hudson Bay. The waters in this district flow north and west, collecting finally in Rainy Lake and draining through the river of the same name into the Lake of the Woods and Lake Winnepeg, and finally entering Hudson Bay through the Nelson River. It was in the country reached by means of this string of connecting waters that the great battle of commercial supremacy in the Northwest was fought in the early part of the century by the Hudson Bay Company and its younger rival, the Northwest Fur Company. The Hudson Bay people came up the Nelson and carried out their goods for the most part the same way. The Northwest Fur Company came from Lake Superior and went to a great extent through the streams and lakes bordering the Vermilion district down the Rainy River and returned over the same route, although at times an all-Canadian route north of the international boundary was used.

Streams.—The streams of the district are, with one exception, short, narrow, and shallow, and form merely the connections between the numerous lakes. The Kawishiwi[a] River, which runs through T 63 N., Rs. 9, 10, and 11 W., is the exception. This is a fairly long stream, which for a portion of its course is within the southern border of the district. In places it is both wide and deep. It is interrupted, however, by rapids, and is full of widenings which really may be considered as lakes, so that by a strict interpretation it could perhaps be classed with the other strings of lakes. The course of this stream can be followed on the accompanying maps, and an examination of the geologic map shows that it follows the contacts of the various formations occurring in the part of the district in which it runs. The Kawishiwi River is peculiar in certain portions of its course and shows clearly that over a greater portion of its extent it is, as has already been stated, merely a string of lakes. The main stream flows through secs. 20 and 21, T. 63 N., R. 9 W., just below the margin of the area mapped. At this place there is a large island, about 2 miles long, extending northeast-southwest, but not caused, as one would naturally think, by the stream dividing and flowing around both sides of it. It is due to the fact that to the north of the island, in sec. 16, T. 63 N., R. 9 W., there is a lake which has two outlets, and from which the water flows to the southwest and to the northeast. The water running southwest joins the Kawishiwi after flowing about one-fourth of a mile. The water

[a] The Indian name of this river is reported to be Mishiwishiwi, meaning "Big Beaver House River." The Minnesota maps give it as Kawishiwi, and it is known in local parlance as the Cashaway.

flowing northeast follows this course for a short distance, then turns to the southwest and joins the Kawishiwi about 2 miles from the outlet of the lake.

Somewhat farther west there is a striking case of the division of the stream and the formation of an island in this way. The island here referred to is only partly included in the area shown on the present map, and the reader is referred to plate 78, Vol. IV, Geological and Natural History Survey of Minnesota, Final Report, where the course of the river around it is shown. The area is briefly described by Grant, page 400 of the same report. Extending through T. 62 N., Rs. 10, 11, and 12 W., is a large island, with a maximum length of about 11 miles and a breadth of 4 miles, which is completely surrounded by the north and south branches of the Kawishiwi and the lakes which are developed in their courses. The water of the main Kawishiwi divides in sec. 26, T. 63 N., R. 10 W. A part of it, forming the north branch proper, flows nearly due west a distance of about 8 miles, in which distance it descends about 70 feet. That portion forming the south branch flows south and southwest, then north and northeast. The total length of the South Kawishiwi is about 30 miles, and it descends 70 feet before it joins the first or the north branch.

Lakes.—The lakes are the most characteristic drainage feature of the Vermilion district. They are a source of great relief to the geologist, who, wearied with a day's tramp through the brush on the hills, returns to his birch-bark canoe and paddles back to his camp, situated at some pleasant spot on the shore. They likewise afford a constant source of pleasure to the traveler through the district, whose interest is aroused by the rapid changes from a narrow lake with rocky cliffs to others showing broad reaches of open water studded with green islets. This interest is sustained by the fact that each succeeding lake entered affords something new to attract the attention. The scenery, although all of the same general character, is constantly changing in its details. Occasionally a moose or caribou may be seen swimming from shore to shore, and the fishing is generally excellent. The lakes vary greatly in size. Vermilion Lake, the largest, covers about 70 square miles, excluding islands, more than fifty of which are in the area mapped. Other large lakes are Basswood (Bassimenan or Whitewood) Lake and Saganaga Lake, which border the district. From these large ones the lakes grade in size down to mere ponds. A rough count gives 250 lakes within the region shown on the topographic map.

The lakes are somewhat scattered in the western portion of the district, but are far more numerous in the eastern part. There are many small ones with no visible surface outlet, and these are usually completely surrounded by drift. The lakes lie in basins that trend northeast-southwest, and with their short connecting streams they constitute the main routes of travel through the district. Indeed, were it not for them the district could be traversed only with extreme difficulty. A trip north and south across the district is very arduous, as the trails, if any exist, are long and over high, rough ridges, while the waterways are so narrow in this direction as to make it seem useless to carry canoes for such long distances, in view of the short distance they can be used, whereas without them such a route would be thoroughly impracticable. On an east-west trip, however, one can start from Tower, and go along the lines of lakes to Gunflint, on the Canadian border, by canoes—a distance of 75 miles in a straight line, and much greater by the route traveled—and on the trip make only about 20 portages, not aggregating in all over 4 miles. A number of these portages, moreover, are mere lift overs, from 10 to 50 yards long, and others are the demies or petites décharges of the French voyageurs, where it is only necessary to lighten the canoe in order to float with safety over the bowlders.

Differences in water level.—The differences in level of the bodies of water in the district are very considerable; but, owing to the fact that these differences are rarely shown by bodies of water near one another, there are no high falls. The highest lake above the level of the sea is a small one very near the top of one of the highest hills in sec. 20, T. 65 N., R. 4 W., in the eastern part of the district. This is at an elevation of 1,880 feet. Basswood Lake, the lowest body of water in the district, is 1,300 feet above sea level. The difference of these extremes, separated by 26 miles, is only 580 feet.

Water power.—The streams connecting these lakes have for the most part unimportant rapids in them. In a number of places, however, considerable water power can be developed, as, for instance, at the Kawashachong Falls, where the Kawishiwi empties into Fall Lake; at the Pipestone Falls on Newton Lake; at several places on the upper Kawishiwi in secs. 30, 28, and 24, T. 63 N., R. 10 W.; in secs. 19 and 20, T. 63 N., R. 9 W.; in sec. 1, T. 64 N., R. 9 W., on Basswood Lake; at the falls between White Iron and Birch lakes; and at the falls between White Iron and Stuntz lakes, just below the south edge of the district. Of these the most accessible and the best, and hence the ones most likely to be used, are the falls of the Kawashachong, with a fall of about 32 feet, and Pipestone Falls, and the falls between White Iron and Birch lakes. By a small dam at the outlet of many of the lakes, large reservoirs could be formed and considerable water power developed at little cost.

Origin of the lakes.—General statements are very frequently made concerning the lake regions of the Northern States lying within the limits of the glacial drift, especially of the lake regions of Wisconsin and Minnesota, which would lead the casual reader to suppose that all of the lakes in these regions owe their origin solely to the agency of the drift, i. e., that they are mere depressions within the general drift mantle which have been filled with water. This is certainly true for a great number of the lakes in the drift-covered portion of North America. In the case of the Vermilion district of Minnesota, however, this simple mode of origin can be predicated of but few of the lakes, and those are all small. The greater number of the lakes have had a mixed mode of origin; they owe their existence to pre-Glacial erosion, which scooped out deep valleys, and then to the drift, which left dams across these valleys at intervals. It is very probable that glacial erosion was also active in widening and deepening these pre-Glacial valleys, changing V-shaped into U-shaped valleys. Many of the lakes empty over rocky rims. They occupy basins formed by the damming of pre-Glacial valleys by drift, and their present outlets are higher than the original mouth of the valley. However, the writer nowhere observed rock-basin lakes which he could interpret as due to glacial erosion.

The lakes in the western part of the district can be readily divided into those which owe their present location and existence solely to glacial action, and those which owe their existence to Pleistocene glaciation, but whose present location and configuration are chiefly due to the geologic structure of the pre-Glacial rocks and to pre-Glacial drainage. To the first kind belong, among others, the oval or irregular lakes lying in the deep morainal drift which stretches northeast-southwest through T. 61 N., R. 14 W., and T. 62 N., R. 13 W.

Lake Vermilion is a good illustration of the second kind of lake. Its very irregular outline, with its islands and bays, is due chiefly to the geologic structure and differential erosion of the various closely folded rocks touching its shores. The reader is referred to the statement on page 432, wherein attention is called to the fact that in many cases the islands are the crests of anticlines of harder rocks, the basins between being in the slate synclines; and also to the statement that the large bays on the east end of the lake are found invariably to be in the younger Lower Huronian rocks. However, even in this western part of the district where the drift is relatively heavy, the general trend of the long direction of the lakes corresponds to the trend of the structural features; that is, it is about N. 60°-80° E. These lakes in the western portion of the district have relatively large drainage basins, and are usually bordered by low shores clothed with small second-growth timber. Near these shores and back from them within their drainage basins one very commonly finds swamps of considerable extent, which are not very much above the lake level. The water of the lakes is clear but is almost invariably tinged by the coloring matter brought in from these tributary swamps. This coloring varies much in intensity in the different lakes, and although the writer's observations extended over only a portion of the year—the months of July, August, September, and into October—it was very noticeable that the intensity of the coloring varied in the same body of water, being less in the late fall, when the water was low, than in the early summer, just after the heavy rains, when the swamps and streams were flooded. Sometimes the organic coloring matter is so plentiful that a bucketful of the water shows a decided brown color. Such waters, although clear, are not very transparent. It is almost impossible at times to distinguish dark bodies 6 inches below the surface of such water. Canoeing in smooth water of this nature is somewhat hazardous; the bowman, even when keeping a sharp lookout, can scarcely see the reefs and snags in the water until he is upon them, whereas in rough water their presence is shown by the way in which the water breaks on them.

The lakes in the eastern part of the district offer a striking contrast to those in the western portion which have just been described. They are, with the exception of some of the largest lakes, almost uniformly long and narrow, are surrounded by high and bare rocky cliffs, and lie in distinctly structural basins. Later a number of instances will be cited (p. 432) to show the relationship of the distribution of the lakes to the various structural features of the district; here only two will be mentioned. The lakes in secs. 7, 8, and 9, T. 65 N., R. 6 W., are separated by barriers of glacial drift. The depression in which they lie was evidently determined by the structure of the slates, and is clearly of pre-Glacial origin. The existence of this string of lakes is due to the low drift barriers in which the connecting streams are now cutting. The most striking instance which the writer has observed of this relationship of the lakes to the structure is seen in the string of lakes just north of the international boundary known as That Mans, This Mans, Agawa, and the Other Mans lakes. They lie in a great depression in a syncline of slates, and, like those first mentioned, are separated by barriers of drift.

The lakes in the eastern part of the district have, with a few exceptions, very small drainage areas, and but few swamps of any size are tributary to them. Consequently the organic matter which colors the water of the lakes west is wanting, and as a rule the water is beautifully clear and transparent.

A simple sounding apparatus was used for one season with a view to getting the depths of the lake basins. This apparatus consisted of an oiled silk fishing line, with knots 1 meter apart, wound on a large reel, with a three-fourths pound lead plumb bob attached to the free end. The reel was screwed to an arm of light wood. One end of this arm was fastened to a crossbar in the bow of the canoe; the other end, on which the reel was screwed, was free to swing. When the reel was not in use this arm lay close to the left side of the canoe and was suspended from a hook, which kept the reel in place and prevented it from unwinding. When the reel was to be used the arm was swung in front and to the right of the man in the bow, and rested on the gunwale of the canoe. The reel was thus suspended over the water, and soundings could readily be taken and the approximate depths read by counting the knots and estimating the fractions of meters. By this means soundings were taken in a number of the lakes. These showed that the lakes in the western part were shallow. For instance, Lake Vermilion, the largest body of water in the district, gave in two places a depth of 10 meters. The average depth of the lake would be much nearer 6 meters. In contrast to this the narrow, clear-water lakes in the eastern portion of the district, those with high, rocky shores, were found to be deep. These are the lakes in which the trout and bass are most abundant and show best their fighting qualities. A maximum depth of $60\frac{2}{3}$ meters (199 feet) was found near the center of Lake Gobbemichigamma. The writer did not have a chance to sound in some of the other lakes of the district, in which, if one may judge from the character of the water and of the surrounding shores, even greater depths would be found. The soundings taken are recorded on the accompanying maps. The points at which the soundings were made were located approximately by a rough system of triangulation, and are indicated on the maps by dots, adjacent to which are placed the figures giving the depth in meters.

Plankton.—During the season of 1899 a seining apparatus was carried and collections of the plankton of thirty of the lakes of the Vermilion district were made. The lakes from which the specimens were taken were scattered from the western to the eastern part of the district, and, it would seem, should give a fair idea of the general character of the plankton of this district. These collections were given to Dr. E. A. Birge, of the University of Wisconsin, for study. He reports as follows: "The collections made by Mr. Clements have been examined. They contain very few Crustacea and no species except those whose presence in these lakes would be a matter of course, since they belong to genera and species very widely distributed on this continent. In view of these facts, a more detailed report does not seem advisable."

EXPOSURES.

In spite of the glacial drift, the rocks are very well exposed. This is due to the fact that, as before stated, the drift was originally not very thick, and that since its deposition it has been considerably removed. It is also due to the presence of the great number of lakes, excellent exposures of the rocks appearing around their shores and upon the small, rocky islands dotting their surfaces. For example, within the immediate vicinity of Vermilion Lake, on the islands within this lake, and around its shores, where drainage has been especially effective, the rocks rise up in bare hills. The eastern part of the district beyond Moose Lake contains also vast areas in which clean rock surfaces are exposed nearly everywhere, and many of these exposures are of very large size. Between Tower and Moose Lake there are a number of square miles in which the drift deposits are so deep—this is especially true in the area overlain by the Vermilion moraine—that but few exposures could be found. Moreover, within this area of deep drift the forest growth is especially luxuriant, and this tends to conceal those exposures that do exist. As a consequence, the difficulty of determining the structure of these areas is greatly increased, and the results are less reliable than for other portions of the district.

FORESTS.

With respect to the forests also the Vermilion district may be divided into two contrasting areas, a western and an eastern. These areas are separated approximately by a line drawn south from the international boundary at the western end of Knife Lake, through the eastern end of Ensign or Iron Mountain Lake, across the north side of Snowbank Lake to Moose Lake, and then through the eastern end of North Twin (or North Triangle) Lake to the Kawishiwi River.

The western area is to a considerable extent heavily wooded with old forests of mixed growth. On the whole, the hard wood, especially birch, seems to predominate; but scattered through the hard wood there are large areas of white pine (*Pinus strobus*) and Norway or red pine (*Pinus resinosa*). The value of these forests at present is chiefly due to these conifers. With the birch are found some poplars and scattering soft maples, jack pines black pine (*Pinus banksiana*), spruce, and balsam fir. Tamarack (hackmatack, or American larch) and white cedar (arbor vitæ) are also present in varying quantity. The undergrowth consists of smaller birch and poplar, soft maple, mountain ash, black ash, willow, alder, hazel, pin and choke cherry, jack pine, balsam fir, spruce (the last two in places forming almost impenetrable thickets), ground hemlock, the high-bush cranberry, a viburnum (*Viburnum opulus*), June berry or service berry (*Amelanchier canadensis*), and some other less important kinds. In some portions of this western area, especially south of Eagle Nest Lakes, southeast of Fall Lake, near the North and South Twin lakes, and south and west of Pine Lake, the country takes on the aspect of a true pinery. It may be noted here that the above-mentioned areas are the ones in which the drift is especially heavy. Thus one may see the intimate relationship existing between the geology of the district and its forest growth. In these areas red and white pine is the chief growth, with the former rather in the ascendency. There is very little undergrowth in these places, and this is chiefly cherry, balsam, spruce, and ground hemlock. Extensive lumbering operations are carried on in these pineries, and in a very few years the pine will have been cut from most of the large tracts. It will then probably be but a year or two at the most before fire will get into the old pine slashings, and any isolated uncut tracts will thereby be destroyed, as will also adjacent hardwood areas.

Scattered through this western area are large tracts which have been burned over one or more times within the last ten to twenty years. In some places the fire was so severe as to destroy the humus as well as the timber. As a consequence of the removal of these protections, the major portion of the soil, and even in some cases the subsoil, has been washed into the valleys, and the hills are now practically bare rock. Such an area is that known as the "Burned Forties," in secs. 23 and 24, T. 62 N., R. 15 W. Where the soil only was removed it has required some time for the subsoil to reach a condition suitable for plant growth, and the hills in such areas are covered only with grass, weeds, and stunted poplars, birch, and jack pine. In other areas the fire occurred so long ago that sufficient soil has accumulated to support a dense growth of poplar, birch, and jack pine, which has reached fair size. In some places in such burned areas the second growth is almost exclusively poplar; in other localities the jack pine or birch may predominate. The usual history of such an area after it has been burned is as follows: The year after the fire has run through the forest there is always a heavy growth of fireweed (so called in that region)—mare's tail—which springs up. This is soon succeeded by poplar, cherry, birch, jack pine, and rarely seedling white and Norway pine. As a result of the deadening of the original forest trees and their consequent weakening, they very readily succumb to the strong winds. They are blown down, and this fallen timber, with the dense second growth that springs up between the recumbent trunks, renders such areas extremely difficult to traverse. Not many years elapse before this second growth is swept by fire, and in its turn falls and is replaced by a third growth. The repetition of such occurrences renders it increasingly difficult to traverse such burned country unless the fire has been very recent and of sufficient intensity to destroy completely both standing and fallen timber. An occasional rotted and partly burned log of large size in the midst of the pines seems to indicate that long ago fires ran through even those areas in which the present forests are frequently spoken of as the original growth, and destroyed an earlier forest then existing.

This northern country offers obstructions to the explorer such as can probably be met with elsewhere only in tropical countries. It is comparatively easy to travel through the forests of standing Norway and white pine, for here one finds but sparse undergrowth; but only a very small part of the district is covered by such open forest; the greater portion, especially in this western part, is covered by exceedingly dense forests of birch, balsam, and jack pine, with undergrowth that is almost impenetrable in places. Between the areas of high ground covered with the above-mentioned forest growth there lie some swampy areas of tamarack and cedar and open muskegs. During wet years, many of these swamps are flooded, so that in crossing them one wades in water 2 to 3 feet deep. Windfalls have destroyed vast patches of timber and have left the trunks piled upon one another in inextricable confusion, and a second growth in places adds further to the entanglement and increases the difficulties of the traveler. One inexperienced in a country of this character would feel that the task were well-nigh hopeless were he called upon to leave the canoe routes and beaten trails and explore this wilderness. It sometimes requires two hours to advance a mile, and to run a line 5 miles in length and explore the area for a few hundred yards on both sides is a good day's work.

In this western portion of the district there are a number of very extensive wild cranberry marshes and other marshes that would be suitable for the cultivation of cranberries. There seems, indeed, to be no good reason why these marshes should not be improved and cranberries grown upon them for the market. In other States such marshes have proved a good investment, and it would seem that a good opportunity for their development is offered in this district.

The eastern half of the Vermilion district may be spoken of as the burned area. In it there are but a few isolated and very small patches of large timber. This portion of the district seems to have been frequently swept by fires, and at present the growth covering it is, with few exceptions, very small. It is probable that the character of the ground has been a prominent factor in determining the size of the second growth. This portion of the district as a whole is very rocky, and the drift and the soil are much thinner than to the west. The timber is the same as that which occurs farther west, with the difference that, since it is nearly all second growth, poplar, jack pine, and birch predominate, in the order given. In some places within this area the fire has been so intense that even the swamp growth has been destroyed, and in place of the original cedar swamps we now find grassy meadows. There is no way of determining accurately just when this area was denuded of its forests. On the Government plats there is a note to the effect that the country near Gunflint Lake was burned over in the sixties. In some places the section corners are marked on second-growth trees, showing that the burning took place a number of years prior to the time that the region was surveyed. In other places the second-growth birch is at least twenty years old, and here no survey lines of any kind were to be found. On the other hand, there is abundant evidence that fires have run over portions of the area since it was surveyed, for large trees with the marks of the corners and quarterposts, and the bearing trees with their marks on them, have been scorched since these marks were made; and, indeed, in many cases, the marks themselves have been nearly obliterated.

SOIL.

The soil throughout the district is thin, but what there is, being of glacial origin, is of very good character and lends itself readily to cultivation. In the valleys the soil has accumulated in places to considerable depth, and where some of the swamps have been drained and properly treated the crops produced are excellent. However, farming is injured by the climatic conditions, which are unfavorable to the growth and maturity of all but a few crops. Hay can be successfully raised. Potatoes, cabbage, and rutabagas of excellent quality can also be grown, and all of these, especially the hay, bring good prices. Suitable land for farming on a large scale is found in but few places. On some natural meadows in dried lake basins and along the margins of the streams and lakes good crops of hay are made.

GAME AND FISH.

This portion of Minnesota is fairly well stocked with game. Moose, deer, and bear were seen repeatedly. In many places the swamps are traversed by deep cut, recent moose trails, and occasionally there were found small areas so tramped and torn by these animals as to resemble a cattle yard. Moose must be fairly abundant, therefore, although no great number were seen, this being due chiefly to the fact that the party made no attempt to go quietly through the woods. The animals were frequently heard crashing through the underbrush. Only one caribou was seen, though in portions of the district their tracks and runways were common.

Pickerel,[a] wall-eyed pike,[b] bass, the namaycush or lake trout, and whitefish are the kinds of fish most used for food, and occur in abundance, about in the order given. Many of the lakes are teeming with fish, but they are usually the least desirable kind, pickerel and perch. These can be obtained in all of the lakes, and they are so common and relatively such a poor game and food fish that the fisherman ordinarily throws them back into the lake with disdain. Usually, however, he first kills the pickerel, as they are the recognized enemy of the game fish. Pike are not so abundant as pickerel, but they are found in most of the lakes. Bass occur in only a few, but where found they are in fairly large numbers. Trout (*Salvelinus namaycush*) are confined almost exclusively to the deep lakes in which the water is uncolored, although they by no means occur in all such lakes. Since these conditions are most commonly fulfilled in the eastern portion of the district and in the lakes along the international boundary and just across the boundary on Hunters Island, the trout are most common in the eastern portion of the Vermilion district. In exceptional cases lake trout were found in some of the lakes with colored water—for example, Ogishke Muncie—and these were slightly different from the trout in the lakes with uncolored water. They are considerably darker in color and appear to have proportionally heavier bodies and smaller heads. They give the impression of being a heavier and slower fish In the streams and lakes from Peter Lake east to Fay (Paulsons) Lake trout were caught which seemed slightly different from the normal lake trout They are called mountain trout by the woodsmen. They

---

[a] Pickerel is the name commonly applied to the true pike (*Esox lucius*) throughout this State, as well as in Wisconsin. It is easily discriminated from the wall-eyed pike by its shovel-shaped nose and the light spots on the dark background of the body. It is a fish which lives in sluggish waters, among the weeds, and very near the surface of the water generally. It is very slimy and has a disagreeable, strong, fishy odor. The flesh is soft in summer.

[b] The wall-eyed pike (*Stizostedion vitreum*), or pickerel, as it is sometimes called in this region—sometimes dory and jack-fish—is an excellent food fish, with firm, well-flavored, white flesh. It has a golden-yellow color on the sides of the belly, grading up into the darker color of the back, with dark mottlings. These mottlings also occur on the fins.

were not carefully studied, so no good detailed description can be given of them. They seem from general appearance to be more nearly like the ordinary speckled brook trout (*Salvelinus fontinalis*). Some of the markings on the brownish back resemble those on the speckled trout, and they have crimson spots on their sides, but they are in other respects different from these. This is probably one of the numerous varieties of the lake trout. According to the repeated experience of members of the party who, for three different seasons and at different times during those seasons, had fished in the same lakes, the fish caught in the same lake usually run about the same size, showing very slight variations indeed.

White-fish (*Coregonus clupeiformis*) are abundant in a number of the lakes, but since they are caught only in nets they are not to be considered by the sportsman, although they are very important and very delicious as food. They have been netted on Basswood for many years, and shipped to southern Minnesota markets. They also occur in Vermilion, Saganaga, Knife, Otter Track, Ogishke Muncie, and other lakes.

CULTURE.

There are four towns in the Vermilion district—Tower, Soudan, Ely, and Winten. Tower is the westernmost town of the district, and is situated on Vermilion Lake. It was settled in 1882 (at that time there was one log cabin there), and according to the Twelfth Census (1900) has 1,366 inhabitants. These depend almost exclusively for employment upon lumbering operations, a sawmill, and the mines of Soudan. All of the stores and saloons of this portion of the district are located in Tower, and they supply the people of Soudan as well as the people within the Tower limits.

Soudan, an unincorporated place, is 2 miles northeast of Tower, at the foot of Soudan Hill. It has grown up around the Minnesota group of mines, and has about 1,000 inhabitants. It is essentially a mining town, and most of the people are recent immigrants with American-born children. The population of the town consists entirely of employees of the Minnesota Iron Company and their families. The company allows no stores or saloons here.

Ely is situated about midway the district, on the south shore of Long Lake. It is the most prosperous town on the range. It has 3,717 inhabitants, who are for the most part employees of the Minnesota Iron Company and their families; in addition there are, of course, a relatively few people who are employed in the usual stores and small industries of various kinds which are essential to the life of a town of this size.

Winten is a small village at the west end of Fall Lake. It is the eastern terminus of the Duluth and Iron Range Railroad. It owes its existence to the presence of two thriving sawmills, which are rapidly cutting all of the timber of this part of the district. There are about 500 people within a radius of a mile from the mills at Winten.

The name Silver City is not infrequently employed in the conversation of explorers and travelers around Ely, and may lead to confusion in the mind of the stranger. The name is applied to the site of an old exploration which, in the sanguine owner's eyes, was the nucleus around which there was to be developed a city of importance. Nothing exists there now; in fact, the writer does not know that a single house was ever built there. The location is at the White Iron Lake portage, in sec. 32, T. 63 N., R. 11 W., and being on one of the canoe routes and frequently used as a camping place, the name is still current among the woodsmen.

The towns just mentioned are connected by the Duluth and Iron Range Railroad, which is the only one that at present gives service in the Vermilion district. Consequently this road handles all of the lumber and ore that is shipped. The eastern end of the district is touched by the Duluth, Port Arthur and Western Railroad, which was projected to connect Port Arthur and Duluth. This road was built from Port Arthur as far west as Paulson's mine at Gunflint, in sec. 28, T. 65 N., R. 4 W. There are a few houses here, but since the abandonment of the mine, no inhabitants. The two termini, Paulson's mine on the east and Winten on the west, have, however, never been connected except by the railroad survey. At present the road within the United States for the 6 miles from the boundary to Paulson's is impassable, the trestles and many ties having been burned. It would require extensive rebuilding before it could be used, and if rebuilt a new route for a part of the way should certainly be selected, as it would be almost impossible to lay out any route that would not be an improvement over some parts of its present location. Wagon roads throughout the district are few in number. Those near the towns are kept in fair condition, but elsewhere they are very poor. Even the county road between Soudan and Ely is poorly kept. Very few branches run off from this road, so that the country to the north and south of it must be reached by means of the few homesteaders' trails that exist, or else by tramping through the woods. East of Winten the traveler can proceed in summer only on foot and by means of canoes.

INDIAN RESERVATION.

On Sucker Point, a large point of land projecting northeast into Vermilion Lake just across the bay from the mill at Tower, there is a reservation which is occupied by the Bois Fort band of the Ojibwa or Chippewa Indians. According to the last report of the Commissioner of Indian Affairs, there were 808 Indians living on this reservation on June 30, 1900. Of these, however, a considerable number really live outside of the reservation, many of them being located in the vicinity of Ely. The Indians are found in large numbers near the reservation only about the Fourth of July, and at the times when the regular Government payments are made. During the winter they are widely scattered over the country, hunting and trapping, and in summer are encamped on the shores of the lakes, where fish and berries are abundant. In 1898 the Government selected a location on Sucker Point and erected thereon a number of commodious buildings to be used for dwellings for the teachers and Indian children and for school purposes, but these Indians are not progressive, and do not take kindly to the advantages offered them by the Government to become educated agriculturists, or otherwise good citizens. They are very apt in acquiring the vices of civilization; and instead of cultivating the available land on their reservation, they prefer to gain a precarious livelihood by hunting, fishing, and trapping. Only a very small portion of the arable land on the point is cultivated.

CHAPTER II.

RÉSUMÉ OF LITERATURE.

The Vermilion district has been studied from a geologic point of view only since the first quarter of the nineteenth century. A number of years before this, however, portions of it had been visited by fur traders. The well-known international boundary canoe route passed part way along its northeast and northern boundary, and has been used since time immemorial. Some of the early fur-traders and explorers kept journals of their travels, and these make mention of this route. The first few pages of this chapter are devoted to a very brief description of the main canoe routes of the district, and of the methods of travel and customs of the fur traders along the boundary route when this northwest country was first opened. The remainder of the chapter consists chiefly of abstracts of articles dealing with the geologic character of the Vermilion district. In this abstract the author of each paper has been allowed, in most cases, to speak for himself. Where, for various reasons, this was not considered best, the attempt has been made in every case to give exactly the author's meaning, although his precise words may not be used. While innumerable details have been of necessity omitted, it is believed that the salient points of the papers reviewed have been noted and that each author's views have been correctly represented. Should it be found in any case that the author's views have not been correctly stated, the fault is due to error in interpretation. In stating the views of the various writers, comments are for the most part refrained from, as discussions of their statements will be found at the proper places in the descriptive part of the monograph.

Throughout the abstracts the writer has followed the spelling of the proper names given in the original article. The great variation in the spelling of these names will be clearly seen if one follows the name through a number of the reports.

In some cases a report or an article may have been preceded by one or more papers discussing the bearing of some of the facts presented in the final report. In such cases the final paper has been abstracted, and references only have been given to the others.

The literature of the Lake Superior region was very fully reviewed by Prof. C. R. Van Hise in Bulletin No. 86 of the United States Geological Survey, and that review has been continued by him and Mr. C. K. Leith up to the present time. The writer has used this material freely, and wishes to make acknowledgment here of the assistance afforded by these reviews.

The abstracts are arranged chronologically, in the order of the publication of the articles abstracted. By following these abstracts critically the reader can acquaint himself with all published articles dealing with the territory. He can follow the development of the views on the geology of the district, which is comparatively difficult of access, and can see how the knowledge concerning it was increased year by year.

HISTORY OF EXPLORATION AND CHARACTER OF THE ROUTES.

The international boundary trends a little south of east and north of west, and forms the eastern, northeastern, and northern boundary of the district for a total length of 75 miles. From Lake Superior to Rainy Lake the international boundary follows a chain of rivers and lakes, crossing necks of land at two places. One of these, known as the Height of Land, is between North and South lakes, and is the divide between the headwaters of Pigeon River, flowing east to Lake Superior, and the waters flowing west to Rainy Lake and finally to Hudson Bay. The other is a narrow strip of land in sec. 24, T. 66 N., R. 6 W., about 600 paces in width at the portage that separates the waters flowing northeast into Saganaga Lake and then northwest around the north side of Hunters Island, so called, from the waters flowing northwest and around the south side of Hunters Island, both of these finally uniting in Lac La Croix. This narrow strip of land, about 600 paces wide at the portage, is all that prevents the body of land, with an area of approximately 1,000 square miles—to which the name Hunters Island was given erroneously, as we now know—from being in reality an island instead of a peninsula.

As is well known, the rivers and chains of lakes marking the international boundary have been for the Indians the main route of travel from Lake Superior into the Northwest from time immemorial. It was this same route that was followed by the fur traders and explorers who first carried civilization to the Indians of the extreme Northwest—a civilization characterized, when first presented to them, by honesty and good morals in minimum amount, and dishonesty, lasciviousness, and rum in maximum quantities. The Vermilion district is traversed for its entire length by a canoe route, which leaves the international boundary route at Gunflint Lake and continues westward. At Vermilion Lake this route joins a canoe route that comes from Rainy Lake, by way of Vermilion River. It then ascends Pike River, crosses the divide—the Giants range—south of Vermilion Lake, and thence continues on down St. Louis River to Duluth, where Lake Superior is reached. The Vermilion district can also be reached from Lake Superior by canoe routes from Grand Marais, Beaver Bay, and other points on the lake shore.

The route along the boundary is, of course, well known to every student of the history of the Northwest, and for one imbued with a love of history as well as nature a pleasanter journey can scarcely be conceived than that which can be so delightfully made in canoe from Grand Portage, on Lake Superior, to Rainy Lake, or farther to the northwest if one chooses.[a]

The easternmost part of the route is known by the name of Grand Portage. This name was at first applied to the portage, 9 miles long, from Lake Superior to Pigeon River, and has since been given to the settlement at the Lake Superior end of the portage. This part of the route is mentioned in the accounts of nearly all of the early explorers, and if they did not use the route they at least visited or heard of the port, as it was one of the most important settlements on the chain of Great Lakes.

The literature dealing with the part of the international canoe route that touches the Vermilion district has not been fully examined, but some pains have been taken to get references to it, descriptions of it, and mode of travel over it from the works of the early explorers. Jonathan Carver[b] mentions the Grand Portage settlement, which he visited, but describes Rainy Lake and the route to it only from hearsay. Alexander Mackenzie,[c] who must have traversed the region a number of times, gives

[a] "The route from Grand Portage to Rainy Lake traverses about 100 miles of distance, the direct line being not far from 70 miles. There are 29 portages. The first, or 'grand portage,' is 8½ miles, the third is 1⅓, the ninth is 1½, and the residue vary from a few steps to a half mile. The total of portages, 15 miles. The water communications are chiefly small lakes of 3 to 10 or 20 feet deep." Hanchett and Clark: Report on Geology of Minnesota, pp. 47–48, 1865. See Vermilion literature references, p. 66 of this monograph.

[b] Travels Through the Interior Parts of North America, by Jonathan Carver, Edition 1778, pp. 106–115.

[c] Voyages from Montreal, on the River St. Laurence, Through the Continent of North America, to the Frozen and Pacific Oceans, in the years 1789 and 1793, by Alexander Mackenzie, London, 1801.

the best description of the route, as well as of the method of travel over it, which the writer has thus far found. As essentially the same method is in use at the present day, with the difference that, since the transport of furs over this route is no longer of importance, the canoes used are not so large and the number of men employed is very much smaller, the description of that portion of the route leading from Lake Superior into the Vermilion district seems to be of sufficient interest to warrant its insertion here in the author's words, with the addition of a few footnotes, added chiefly for the purpose of enabling the reader to identify the lakes by their present names with the lakes as known to Mackenzie. His description of the route is given in connection with his account of the rise, progress, and condition of the fur trade, in which the author was interested as one of the partners of the Northwest Fur Company.

Mackenzie's description of Grand Portage Bay and its surroundings, at the eastern end of the canoe route, is very good. Let us refer to this description and attempt to see the bay as he saw it, surrounded by hills rising to a height of 730 feet, its bosom dotted with canoes and its shores bearing the tents and wigwams of the fur traders and Indians. Back from the shore and on the slope of the hill was the fort, which was occupied by the traders and trusted employees, and in which the goods were stored. The traders with their stores came from Montreal, but we shall not attempt to follow their journey in detail.

A quantity of their goods are sent from Montreal in boats to Kingston, at the entrance of Lake Ontario, and from thence in vessels to Niagara, then overland 10 miles to a water communication, by boats, to Lake Erie, where they are again received into vessels, and carried over that lake up the river Detroit, through the lake and river Sinclair to Lake Huron, and from thence to the Falls of St. Marys, when they are again landed and carried for a mile above the falls and shipped over Lake Superior to the Grande Portage [p. xxxix]. . . . At length they all arrive at the Grande Portage, which is 160 leagues from St. Marys, and situated on a pleasant bay on the north side of the lake. . . .

At the entrance of the bay is an island which screens the harbor from every wind except the south. The shallowness of the water, however, renders it necessary for the vessel to anchor near a mile from the shore, where there is not more than 14 feet water [p. xl].

* * * * * * * *

The bottom of the bay, which forms an amphitheater, is cleared of wood and inclosed, and on the left corner of it, beneath a hill 300 or 400 feet in height, and crowned by others of a still greater altitude, is the fort. picketed in with cedar pallisadoes and inclosing houses built with wood and covered with shingles. They are calculated for every convenience of trade. as well as to accommodate the proprietors and clerks during their short residence there. The North men live under tents; but the more frugal pork eater lodges beneath his canoe. The soil immediately bordering on the lake has not proved very propitious. . . . There are meadows in the vicinity that yield abundance of hay for the cattle; but, as to agriculture, it has not hitherto been an object of serious consideration.

I shall now leave these geographical notices to give some further account of the people from Montreal. When they are arrived at the Grande Portage, which is near 9 miles over, each of them has to carry eight packages of such goods and provisions as are necessary for the interior country. This is a labor which cattle can not conveniently perform in summer, as both horses and oxen were tried by the company without success. . . .

Having finished this toilsome part of their duty. if more goods are necessary to be transported, they are allowed a Spanish dollar for each package; and so inured are they to this kind of labor, that I have known some of them set off with two packages of 90 pounds each, and return with two others of the same weight, in the course of six hours, being a distance of 18 miles over hills and mountains.[a] This necessary part of the business being over, if the season be early they have some respite, but this depends upon the time the North men begin to arrive from their winter quarters, which they commonly do early in July. At this period it is necessary to select from the pork eaters a number of men, among whom are the recruits, or winterers, sufficient to man the North canoes necessary to carry to the river of the rainy lake the goods and provisions requisite for the Athabasca country, as the people of that country (owing to the shortness of the season and length of the road can come no farther) are equipped there, and exchange ladings with the people of whom we are speaking, and both return from whence they came.[b] This voyage is performed in the course of a month, and they are allowed proportionable wages for their services [pp. xliii-xlv]. . . .

* * * * * * * *

The trade from the Grande Portage is, in some particulars, carried on in a different manner with that from Montreal. The canoes used in the latter transport are

---

[a] Further on in his narrative, Mackenzie cites examples of men who have taken seven packages each, and carried them without stopping across a portage one-half league in length [p. lxi.]—J. M. C.

[b] The system of living at Grande Portage was decidedly feudal, and is described by Mackenzie as follows: "The proprietors, clerks, guides, and interpreters mess together, to the number of sometimes a hundred, at several tables, in one large hall, the provision consisting of bread, salt pork, beef, hams, fish, and venison, butter, pease, Indian corn, potatoes, tea, spirits, wine, etc., and plenty of milk, for which purpose several milch cows are constantly kept. The mechanics have rations of such provision, but the canoemen both from the North and Montreal have no other allowance here, or in the voyage, than Indian corn and melted fat" [p. xlvi]. The Indian corn mentioned is hominy prepared at Detroit.—J. M. C.

now too large for the former, and some of about half the size are procured from the natives, and are navigated by four, five, or six men, according to the distance which they have to go. They carry a lading of about thirty-five packages, on an average; of these, twenty-three are for the purpose of trade, and the rest are employed for provisions, stores, and baggage. In each of these canoes are a foreman and steersman—the one to be always on the lookout, and direct the passage of the vessel, and the other to attend the helm. They also carry her whenever that office is necessary. The foreman has the command, and the middle men obey both; the latter earn only two-thirds of the wages which are paid the two former. Independent of these a conductor or pilot is appointed to every four or six of these canoes, whom they are all obliged to obey, and is, or at least is intended to be, a person of superior experience, for which he is proportionably paid.

In these canoes, thus loaded, they embark at the north side of the portage, on the river Au Tourt,[a] which is very inconsiderable, and, after about 2 miles of a westerly course, is obstructed by the Partridge Portage, 600 paces long. In the spring this makes a considerable fall, when the water is high, over a perpendicular rock of 120 feet. From thence the river continues to be shallow, and requires great care to prevent the bottom of the canoe from being injured by sharp rocks, for a distance of 3½ miles to the prairie, or meadow, when half the lading is taken out, and carried by part of the crew, while two of them are conducting the canoe among the rocks with the remainder to the Carreboeuf Portage, 3½ miles more, when they unload and come back 2 miles and embark what was left for the other hands to carry, which they also land with the former, all of which is carried 680 paces, and the canoe led up against the rapid. From hence the water is better calculated to carry canoes, and leads by a winding course to the north of west 3 miles to the Outard Portage,[b] over which the canoe, and everything in her, is carried for 2,400 paces. At the farther end is a very high hill to descend, over which hangs a rock upward of 700 feet high. Then succeeds the Outard Lake,[c] about 6 miles long, lying in a northwest course, and about 2 miles wide in the broadest part. After passing a very small rivulet they come to the Elk Portage,[d] over which the canoe and lading are again carried 1,120 paces, when they enter the lake of the same name, which is a handsome piece of water, running northwest about 4 miles, and not more than 1½ miles wide.* They then land at the Portage de Cerise,[e] over which, and in the face of a considerable hill, the canoe and cargo are again transported for 1,050 paces. This is only separated from the second Portage de Cerise by a mud pond[f] (where

* Here is a most excellent fishery for whitefish, which are exquisite.

[a] According to Coues, this is the abbreviation for Tourtes. This was even then known as Pigeon River.—J. M. C.

[b] Known now as Fowl Portage.—J. M. C.

[c] Called on Thompson's map, 1792, Goose Lake. Now called South Fowl Lake.—J. M. C.

[d] Called now and also on Thompson's map Moose Lake and Portage.—J. M. C.

[e] Big Cherry Portage now.—J. M. C.

[f] Mud Portage.—J. M. C.

there is plenty of water lilies) of a quarter of a mile in length, and this is again separated by a similar pond from the last Portage de Cerise,[a] which is 410 paces. Here the same operation is to be performed for 380 paces. They next enter on the Mountain Lake, running northwest by west, 6 miles long and about 2 miles in its greatest breadth. In the center of this lake and to the right is the Old Road, by which I never passed; but an adequate notion may be formed of it from the road I am going to describe, and which is universally preferred. This is, first, the small new portage[b] over which everything is carried for 626 paces, over hills and gullies. The whole is then embarked on a narrow line of water[c] that meanders southwest about 2½ miles. It is necessary to unload here, for the length of the canoe, and then proceed west half a mile to the new Grande Portage, which is 3,100 paces in length, and over very rough ground, which requires the utmost exertions of the men, and frequently lames them; from hence they approach the Rose Lake, the portage of that name being opposite to the junction of the road from the Mountain Lake. They then embark on the Rose Lake, about 1 mile from the east end of it, and steer west by south in an oblique course across it, 2 miles; then west-northwest, passing the Petite Perche to the Marten Portage, 3 miles. In this part of the lake the bottom is mud and slime, with about 3 or 4 feet of water over it; and here I frequently stuck a canoe pole of 12 feet long without meeting any other obstruction than if the whole were water. It has, however, a peculiar suction or attractive power, so that it is difficult to paddle a canoe over it.[d] There is a small space along the south shore where the water is deep, and this effect is not felt. In proportion to the distance from this part, the suction becomes more powerful. I have, indeed, been told that loaded canoes have been in danger of being swallowed up, and have only owed their preservation to other canoes, which were lighter. I have, myself, found it difficult to get away from this attractive power, with 6 men and great exertion, though they did not appear to be in any danger of sinking.

Over against this is a very high, rocky ridge, on the south side, called Marten Portage, which is but 20 paces long, and separated from the Perche Portage, which is 480 paces, by a mud pond covered with white lilies. From hence the course is on the lake of the same name,[e] west-southwest 3 miles to the height of land, where the waters of the Dove or Pigeon River terminate, and which is one of the sources of the great St. Laurence in this direction. Having carried the canoe and lading over it,

---

[a] Little Cherry Portage.—J. M. C.

[b] Watab Portage on Minnesota geological survey maps.—J. M. C.

[c] This is Rove Lake.—J. M. C.

[d] This phenomenon is very familiar to every one who has used a canoe. After paddling over one of these muddy bottoms, apparently barely making the canoe move with the greatest exertion, there is a remarkable sense of relief and an increase in the rapidity of the canoe's motion when there is a change to a sandy or gravelly bottom. An increase in depth of the water between the top of the mud and the bottom of the canoe will have essentially the same effect. The cause of this is that the canoe is actually floating in a thin mud, and the friction between this mud and the canoe is very much greater than between the clear water and the canoe.—J. M. C.

[e] Now called South Lake.—J. M. C.

679 paces, they embark on the lake of Hauteur de Terre,*[a] which is in the shape of an horseshoe. It is entered near the curve and left at the extremity of the western limb, through a very shallow channel, where the canoe passes half loaded for 30 paces with the current, which leads through the succeeding lakes and rivers and disembogues itself by the River Nelson into Hudson's Bay. The first of these is Lac de Pierres à Fusil,[b] running west-southwest, 7 miles long and 2 wide, and making an angle at northwest 1 mile more, becomes a river for half a mile, tumbling over a rock and forming a fall and portage, called the Escalier,[c] of 55 paces; but from hence it is neither lake or river, but possesses the character of both, and ends between large rocks, which cause a current or rapid, falling into a lake pond for about 2½ miles, west-northwest, to the portage of the Cheval du Bois.[d] Here the canoe and contents are carried 380 paces between rocks; and within a quarter of a mile is the Portage des Gros Pins,[e] which is 640 paces over a high ridge. The opposite side of it is washed by a small lake 3 miles round; and the course is through the east end or side of it, three-quarters of a mile northeast, where there is a rapid. An irregular, meandering channel, between rocky banks, then succeeds for 7½ miles to the Maraboeuf Lake, which extends north 4 miles, and is three-quarters of a mile wide, terminating by a rapid and décharge of 180 paces, the rock of Saginaga being in sight, which causes a fall of about 7 feet and a portage of 55 paces.

Lake Saginaga takes its name from its numerous islands. Its greatest length from east to west is about 14 miles, with very irregular inlets; is nowhere more than 3 miles wide, and terminates at the small portage of La Roche,[f] of 43 paces. From thence is a rocky, stony passage of 1 mile to Prairie Portage, which is very improperly named, as there is no ground about it that answers to that description, except a small spot at the embarking place at the west end. To the east is an entire bog, and it is with great difficulty that the lading can be landed upon stages, formed by driving piles into the mud, and spreading branches of trees over them. The portage rises on a stony ridge, over which the canoe and cargo must be carried for 611 paces. This is succeeded by an embarkation on a small bay,[g] where the bottom is the same as has been described in the west end of Rose Lake, and it is with great difficulty that a laden canoe is worked over it, but it does not comprehend more than a distance of 200 yards. From hence the progress continues through irregular channels, bounded by rocks, in a westerly course for about 5 miles to the little

*The route which we have been traveling hitherto leads along the high, rocky land or bank of Lake Superior on the left. The face of the country offers a wild scene of huge hills and rocks, separated by stony valleys, lakes, and ponds. Wherever there is the least soil it is well covered with trees.

[a] Now called North Lake.—J. M. C.

[b] Gunflint Lake.—J. M. C.

[c] Little Rock Portage.—J. M. C.

[d] Wood Horse Portage.—J. M. C.

[e] Pine Portage.—J. M. C.

[f] This leads from Saganaga into Swamp Lake.—J. M. C.

[g] At east end of Otter Track Lake.—J. M. C.

Portage des Couteaux, of 165 paces, and the Lac des Couteaux, running about southwest by west 12 miles, and from a quarter to 2 miles wide. A deep bay runs east 3 miles from the west end, where it is discharged by a rapid river, and after running 2 miles west it again becomes still water. In this river are two carrying places, the one 15 and the other 190 paces. From this to the Portage des Carpes is 1 mile northwest, leaving a narrow lake on the east that runs parallel with the Lake des Couteaux, half its length, where there is a carrying place which is used when the water in the river last mentioned is too low. The Portage des Carpes is 390 paces, from whence the water spreads irregularly between rocks 5 miles northwest and southeast to the portage of Lac Bois Blanc, which is 180 paces. Then follows the lake of that name,[a] but I think improperly so called, as the natives name it the Lake Pascau Minac Sagaigan, or Dry Berries.

Before the smallpox ravaged this country and completed what the Nodowasis [Sioux] in their warfare had gone so far to accomplish, the destruction of its inhabitants, the population was very numerous; this was also a favourite part, where they made their canoes, etc., the lake abounding in fish, the country round it being plentifully supplied with various kinds of game, and the rocky ridges, that form the boundaries of the water, covered with a variety of berries.

When the French were in possession of this country they had several trading establishments on the islands and banks of this lake. Since that period the few people remaining, who were of the Algonquin Nation, could hardly find subsistence; game having become so scarce that they depended principally for food upon fish and wild rice, which grows spontaneously in these parts.

This lake is irregular in its form, and its utmost extent from east to west is 15 miles; a point of land called Point au Pin, jutting into it, divides it in two parts; it then makes a second angle at the west end to the lesser Portage de Bois Blanc, 200 paces in length.

This description will serve to give the reader unacquainted with the area some knowledge of the character of the route and of the character of the voyageurs and Indians. Further interesting details of the international canoe route and the methods of travel can be obtained from Alexander Henry's and David Thompson's journals for the years 1799–1814, pp. xlvii–liii.[b]

---

[a] Commonly called at present Basswood Lake.—J. M. C.

[b] New light on the early history of the Greater Northwest. The manuscript journals of Alexander Henry, fur trader of the Northwest Company, and of David Thompson, official geographer and explorer of the same company, 1799–1814. Edited by Elliott Coues. New York: Francis P. Harper, in three volumes 1897.

GEOLOGICAL LITERATURE.

1825.

BIGSBY, JOHN J. Notes on the geography and geology of Lake Superior: Quarterly Journal of Science, Literature, and Arts, Vol. XVIII, 1825, pp. 1-34, 222-269, with map.

Bigsby, in 1825, describes the rocks at many points along the north shore of Lake Superior. He also follows the old route from Lake Superior to the Lake of the Woods for 430 miles, and observes an alternation of chloritic greenstone and amphibolitic granite. Near and on the Lake of the Woods the greenstone passes into gneiss and mica-slate which is penetrated by graphic granite.

This statement concerning Bigsby's observations is obtained from Bulletin U. S. Geological Survey No. 86, p. 51. The article to which these statements were credited not having been found, they can not be verified; and whether any further observations were made by Bigsby in the area included in the Vermilion district has not been learned.

1841.

HOUGHTON, DOUGLASS. [Fourth] Annual Report of the State Geologist, 1841. State of Michigan, House of Representatives, No. 27. Reprint in "Memoirs of Douglass Houghton, First State Geologist of Michigan," by Alvah Bradish, Detroit, 1889; 302 pages.

In this report Dr. Houghton refers incidentally to that portion of Minnesota which extends along the international boundary, a part of which is included in this monograph, in the following words:

> The hills rise in broad and somewhat knobby steppes or plateaus, to heights varying from 400 to 1,200 feet above the lake, and the summits of these hills are usually not farther inland than from 10 to 20 miles. The rocks of the hills are very frequently bare over considerable areas, and the valleys containing arable soil are few and very narrow.
>
> The route of the fur trade to the northwest, via Rainy lakes, Lake of the Woods, and Lake Winnepic, was formerly wholly carried on by passing over these hills from a point a few miles west from the mouth of Pigeon River. The trail or portage path passes over a low portion of the range, and finally falls upon Pigeon River, which is ascended to its source, from which, by a series of portages, the sources of the streams flowing northwesterly are reached. The hilly portion of the country, though of exceeding interest in a geological point of view, is the most desolate that could be conceived.

1852.

Owen, David Dale. Report of a geological survey of Wisconsin, Iowa, and Minnesota; and incidentally of a portion of Nebraska Territory. 1852. (Dr. J. G. Norwood's report, pp. 213–418.)

In 1848 Dr. Norwood ascended St. Louis River, and crossing the divide descended Vermilion River to Vermilion Lake. This portion of the river is now known as Pike River. He then crossed the lake and went on down Vermilion River proper to Rainy River. His observations were not numerous. On the divide, the Missabé Wachu (Big Man Hills) or Giants range, he observed syenitic granite associated with gneiss. As Vermilion Lake was approached, outcrops of slaty hornblende rock, micaceous clay slate, and siliceous slate appeared in the banks and bed of the river, forming riffles and falls. On the south side of Vermilion Lake talcose and mica-slate and micaceous schists were exposed. On the north side of the lake, at the outlet, and continuing on along the outlet, mica-slate and granite were found. He notes that the general trend of the ridges is east-northeast and west-southwest (p. 313). Structurally, he considers the northeast part of Minnesota (p. 333) to consist of northeast-southwest alternating anticlinal and synclinal folds, rivers sometimes occupying the synclinal valleys. A range of greenstone, beginning at the great bend of St. Louis River and running northeast (N. 30° E.), forms a true anticlinal axis, the line of elevation crossing the boundary line between the sources of Arrow Lake and Mountain Lake (p. 336).[a]

In 1849 Dr. Norwood followed the international boundary from Pigeon River to Saganaga Lake. He mentions the occurrence of siliceous slate and hornblende and ferruginous rocks on Gunflint Lake, and while the statement is not perfectly clear, he seems to have the idea that these have been disturbed by the intrusion of the granite, which he observed exposed from Gunflint Lake to Saganaga Lake. This granite forms a range which, if continued on the southwest, he states (p. 417) would pass in the line of the Missabé Wachu (Giants range) and Pokegama Falls on the Mississippi. He thus implies the correlation of the granite of Saganaga Lake with that of the Mesabi range, a position taken by some of the later geologists, as will be seen below. He commends the northwest shore of Lake Superior as

[a] Norwood erred in making this statement, as this axis—the Giants range—crosses the international boundary between Gunflint and Saganaga lakes.

perhaps the best extinct volcanic region in the world in which to study igneous intrusion. It is to be regretted that Owen did not closely follow Norwood's notes in compiling his general map, as the map would then show far more accurately than it does the distribution of the rocks of the Vermillion district as disclosed by Norword's reconnaissance survey.

Sections 1 and 2 on Pl. 2 N of Owen's report have no legend other than that giving a general location, and consequently one can not be absolutely sure of the rock represented. It is clear, however, that Norwood had the idea that the metamorphic rocks in both the Vermillion and the Saganaga area are cut by the granite of the Mesabi range and Saganaga Lake and folded in between the granite ridges.

1861.

Anderson, C. L., and Clark, Thomas. Report on geology: Document No. 12, Minnesota legislature. St. Paul, 1861: 26 pages.

There was reprinted in 1860, by order of the Minnesota senate, portions of the publications of the geological surveys of Wisconsin for 1854 and 1858, which, owing to the juxtaposition of the States, it was thought would equally apply to Minnesota. Mr. Thomas Clark, of Lake City, was chairman of the committee having in charge the publication of this first geological report of the State of Minnesota. The same year that this report was published a commission was appointed, consisting of C. L. Anderson and Thomas Clark, above referred to, to report on the geology of the State and on a plan for a geological survey of the State. This report was sent to the legislature by the governor, who, however, declared himself not ready to advise the commencement of a geological survey.

In the report the commissioners call attention to some of the general geologic features of the State. The only points of interest in connection with the present study of the literature of the region is the recognition of the existence of granite and metamorphic rocks, forming northeast-southwest trending ranges in the northeastern part of the State, and the insistence on the investigation of this area, with the view to determining the existence of metalliferous deposits in the rocks in this region.

1865.

Hanchett, A. H., and Clark, T. Report of the State geologist, Aug. H. Hanchett, M. D., together with the physical geography, meteorology, and botany of the northeastern district of Minnesota, by Thomas Clark, assistant geologist. St. Paul. 1865; 82 pages.

The agitation of the question of the organization of a geological survey of Minnesota evidently had some effect, as is shown in the publication of this report. Among other things, the State geologist reports that "specimens of hematitic specular iron ore were obtained from a heavy deposit said to lay between a lake forming the affluence of the Upper Embarrass River and Vermillion Lake. The precise percentage of commercially pure iron contained in this ore has not been ascertained" (p. 6).

1866.

Eames, Henry H. Report of the State geologist on the metalliferous region bordering on Lake Superior. St. Paul, 1866; 23 pages.

Eames gives merely a brief description of the then known metalliferous rocks of northeastern Minnesota. He mentions the occurrence in the Vermillion district of the siliceous and talcose slates (p. 10) of Vermillion Lake, in the last of which are found auriferous and argentiferous quartz veins and the hematite iron ore (p. 11) of Vermillion Lake, which is associated with quartzose jasperoids and serpentine rocks.

Eames, Henry H. Geological reconnoissance of the northern, middle, and other counties of Minnesota. St. Paul, 1866; 58 pages.

This contains the results of a geologic reconnaissance of the State. It was found that the granite uplifts have their greatest development in the northeastern part of the State. They trend northeast, and reach their greatest altitude at or near the Missabe heights. The most prevalent rocks found in the northern part of the State are granite, porphyry, hornblendic slates, siliceous slates, trap, greenstone, talcose slate, primitive schistose rock, gneiss, and Potsdam sandstone. In the region occupied by these rocks are found immense bodies of magnetitic and hematitic iron ore. In the talcose slates and primitive schistose rock are veins of quartz, carrying auriferous and argentiferous sulphides of iron and copper

In a report by Richard M. Eames, assistant, a number of details of the Vermilion Lake district, chiefly concerning veins, are given, and a geologic map showing the outline of the formation surrounding Vermilion Lake is said to have been prepared and handed in, but does not accompany the published report.

WHITTLESEY, Col. CHARLES. Geology and minerals. A report of explorations in the mineral regions of Minnesota during the years 1848, 1859, and 1864. Cleveland, 1866; 54 pages.

According to Colonel Whittlesey the Minnesota shore of Lake Superior structurally represents the northern edge of a syncline, in the basin of which Lake Superior lies, and we consequently get essentially the same succession of rocks that is found on the southern shore of Lake Superior in Michigan and Wisconsin—a belt of alternating sandstone beds and trap flows, succeeded inland by a belt of trap. These two constitute the series which is known as the Keweenawan. Back of the trap he finds a belt of hornblende rocks, or hornblende-slates, as they are called. This is the Animikie series of the Minnesota geologists.

> Behind the hornblende system is the imperfectly defined region of the granite, syenite, mica slate, siliceous, and talcose rocks, extending to and across the national boundary. The Mesabi range occupies the watershed between the waters of Lake Superior and those of Hudson's Bay. In many cases the syenite and granite appears to be more recent than the metamorphic slates, having all the appearance of intrusive rocks [p. 7].

That part of the Vermilion Lake region, including the rocks just mentioned—the mica-slate, siliceous and talcose slates—which lies to the north of the Mesabi range is described in some detail. Leaving the syenitic Mesabi range he proceeds over the portage trail to Vermilion River (now known as Pike River) and passes in the order given over syenite, "gray, compact quartz," mica-slate, and distinctly layered novaculitic quartzite. Just before entering Vermilion Lake fine-grained micaceous rocks are exposed, and these continue along the western shore, becoming more talcose and slaty as the explorer goes north. The slaty laminæ strike northeast by east, and dip 75°–80° northwest. These slates are also very much jointed, causing the formation of rhombohedral blocks. On the north shore of Vermilion Lake, Colonel Whittlesey saw and recognized clearly the relations of the granite to the sedimentaries, mica and talcose slate, as he calls the rocks. He says, "The granite appears as a protrusion in the slates, and is therefore more recent" (p. 45).

1871.

Kloos, J. H. Article in The Minnesota Teacher, referred to by N. H. Winchell.

Winchell[a] says that Kloos suggests the possibility of the hematitic and magnetitic iron ore at Vermilion Lake being in the lowest member of the Huronian.

Kloos, J. H. Geologische Notizen aus Minnesota: Zeitschr. deutsch. geol. Ges., Vol. XXIII, 1871, pp. 417–448.[b]

In this article (p. 199) Kloos states that he has become acquainted with gneisses and finely crystalline clay slates from Vermilion Lake, which appear to him to belong to the Laurentian. A small rush to this area was caused by the discovery of gold-bearing pyritiferous quartz veins, cutting the metamorphic schists, but did not result in the opening up of productive mines. He farther on mentions having heard favorable reports concerning the iron ores of Vermilion Lake.

1873.

Bell, Robert. Report on the country between Lake Superior and Lake Winnipeg: Geol. Survey of Canada; Report of Progress for 1872 and 1873, 1873, pp. 87–111.

This contains a report (pp. 92–94) of a reconnaissance along a part of the international boundary from Gunflint Lake to Whitewood[c] (Basswood) Lake, which is included in the Vermilion district. He observed sedimentaries, slates, and dolomite associated with trap on Gunflint Lake. These he correlated with the Lake Superior copper-bearing rocks. They are succeeded to the northwest by the Laurentian granite of Seiganagah (Saganaga) Lake. West of this Laurentian area the route crosses from Poplar Lake (Swamp Lake of the boundary commission map) to Whitewood (Basswood) Lake, a belt of Huronian black to green and gray schists, slates, and quartzites, cut by dikes of trap. The sediments strike S. 15°–30° W., and dip about 80° W. The only rocks observed around the shores of Whitewood Lake are fine-grained gray to reddish-gray syenite.

[a] N. H. Winchell: Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. I, 1884, p. 103.

[b] A translation of this article by N. H. Winchell is published in Geol. and Nat. Hist. Survey of Minnesota, Tenth Ann. Rept., 1882, pp. 175–200.

[c] The usual name given to this lake is Basswood. No basswood was seen by Bell about the lake, however, and my own observation showed me that it is certainly not present in great quantity there. He states that "the lake is said to derive its name Lac de Bois Blanc, or Whitewood Lake, from the whitewood, or balm of Gilead, a kind of poplar" (p. 94).

WINCHELL, N. H. First Ann. Rept. Geol. and Nat. Hist. Survey Minn., pp. 129. Second edition, 1884.

The general distribution of the nonfossil-bearing rocks of Minnesota, referred to as "granitic and metamorphic rocks" (p. 64), is given in this, the first annual report of the second Minnesota survey. It is stated that they occupy a great portion of the northern part of the State. These rocks are regarded as Laurentian and Huronian. At the time of this publication the great deposits of iron ore, which are now of such national as well as local importance, were but little known, as appears from the indefinite statement that "iron ore in unlimited quantities is said to exist in the dividing ridge between Lake Superior and Vermilion Lake" (p. 67).

1876.

WHITTLESEY, Col. CHARLES. Physical geology of Lake Superior: Proc. Am. Assoc. Adv. Sci., Twenty-fourth Meeting, 1875, Part 2, pp. 60–72, with map,

Whittlesey finds nowhere on the American side of the boundary, except at Vermilion Lake, rocks which are like the Laurentian of Canada. The great masses of granite and syenite, around which the Huronian is formed, do not resemble the Laurentian of the Canadian geologists. Between the Canadian and American Huronian there is a very close resemblance. The conclusion of Foster and Whitney that the traps of Lake Superior are of Potsdam age is adopted.

1877.

STRENG, A., and KLOOS, J. H. Ueber die krystallinischen Gesteine von Minnesota in Nord-Amerika: Neues Jahrbuch für Mineralogie. Geologie, und Paleontologie. 1877, pp. 31–56, 113–138, 225–242; translation, by N. H. Winchell, in the Eleventh Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1882, pp. 30–85.

The authors state that "the St. Louis River rises in northeastern Minnesota south of Vermilion Lake, in a region of granite, gneiss, and crystalline slates, which form a branch from the Laurentian formation as it is displayed in the region north of Lake Superior" (p. 36).

1879.

WINCHELL, N. H. Seventh Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1878, 1879, pp. 9–25.

In this we find a report by C. W. Hall on a reconnaissance in the northeastern part of Minnesota. In the summary of geologic results (p. 10) the trend of the formations is stated to be more nearly east and west than it had previously been supposed to be. Hence the formations—

cross the coast line at an acute angle, the later formations being toward the south, and the older along the international boundary line. . . . The formations that compose the coast line[a] . . . seem to be something as follows, in descending order: (1) Metamorphic shales, sandstones, and quartzite. These are cut by dikes, and are interbedded with igneous rock. . . . (2) Ferruginous and aluminous sandstones. These seem to be metamorphosed into a firm basaltiform red rock, as seen in the Palisades and at other points. . . . (3) A quartzose conglomerate, seen at the Great Palisades and Portage Bay Island—probably more properly a part of No. 2. (4) The quartzites and slates of Grand Portage Bay. . . . (5) The jasper, flint, and iron-bearing belt of Gunflint Lake and Vermilion Lake, and of the Mesabi range. (6) The slates and schists which the Canadian geologists particularly designate Huronian. (7) The syenites, granites, and other rocks that have been classed as Laurentian. (8) The igneous rocks, known as the Cupriferous series [p. 10].

Of these, the only ones with which we are much concerned in the Vermilion district are Nos. 4, 5, 6, 7, and 8. It is therefore of interest to learn the relations of these to one another, as given in the report.

Nos. 4, 5, 6, and 7 are probably conformably arranged in succession; at least they have been so seen at places. Nos. 4 and 5 are closely associated, and perhaps the latter is but a local phase of the former, while Nos. 6 and 7 are as closely related, being conformably interbedded and stratified. No. 5 is conformable with No. 6 in the iron district along the southeastern side of Vermilion Lake [p. 11].

1881.

WINCHELL, N. H. Ninth Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1880, 1881.

That portion of this report containing a mention of the northeastern part of the State is apparently merely the published field notes of the State geologist. No attempt is made to reduce these notes to an orderly discussion of the general geology, and the reader must glean such general facts as he can find among the many details given. Thus, apropos of a specimen taken from one of the beds, we learn that a greenish, schistose, porphyritic rock, cut by veins of milky quartz, is found in nearly a vertical attitude on Gunflint Lake. This is supposed to be the Canadian Huronian, and underlies the quartzite and Gunflint beds, apparently unconformably

[a] The northeast-southwest trending coast line of Lake Superior is here meant.

(p. 81). The Knife Lake chloritic or serpentinous quartzite is regarded as Huronian (p. 86).

On the south side of Vermilion Lake are beds of jasper and iron hematite which are regarded as the equivalent of the Gunflint beds. These are conformable with the magnesian schists and slates which are in a vertical attitude. They pass down into the schists, and in places the schists and schistose structure penetrate the jasper and iron (pp. 103–4).

WINCHELL, N. H. The Cupriferous series in Minnesota: Proc. Am. Assoc. Adv. Sci., Twenty-ninth Meeting, 1880, pp. 422–425; Ninth Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1880, 1881, pp. 385–387.

In this description of the Copper-bearing series the impression is made that the series gradually becomes more and more changed and crystalline as one goes away from the shore of Lake Superior. The following relations are mentioned:

The tilted red shales, conglomerates, and sandstones at Fond du Lac . . . . are the same as those associated with the igneous rock all along the shore. They lie there on a white quartz pebbly conglomerate of a few feet in thickness, which lies unconformably on the roofing slates of the Huronian, the same formation which succeeds to the red-rock formation . . . . at Ogishke Muncie and Knife lakes, northwest of Grand Marais [p. 387].

1882.

WINCHELL, N. H. Preliminary list of rocks: Tenth Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1881, 1882, pp. 9–122.

In this report the publication of Winchell's field notes is continued. From them we learn that the flint and jasper formations of Gunflint Lake appear to be in apparent unconformity with the underlying slates and syenites (p. 88). On Ogishkie Muncie Lake is found a great conglomerate.

The conglomerate . . . contains large rounded pieces of the "Saganaga granite," which proves the greater age of that granite and the unconformability of this slaty conglomerate. . . . The conglomerate also here contains red jasper [p. 93].

The descending succession in northeastern Minnesota is given as follows:

(1) The nearly horizontal quartzites and slate. . . . (2) The coarse grit or fine conglomerate. (3) The jaspery and calcareous . . . Gunflint beds. (4) Gray marble. (5) The tilted, slaty conglomerate, and the great conglomerate

about Ogishkie Muncie Lake [bearing Saganaga granite bowlders]. (6) The amphibolite and chloritic slates. (7) Mica schists and alternations of mica schists and syenite. (8) The syenites and granites of Saganaga and Gull lakes [p. 94].

Whether the great quartzite and slate formation (No. 1 above) is the same as the highly tilted slate and quartzite formation which passes into the great conglomerate (No. 5 above) of Ogishkie Muncie Lake is an open question, although there are several things which indicate that they are the same. They have been treated throughout, however, as different terranes. The following are given as the considerations which appear to support their equivalency:

(*a*) Where the horizontal slates approach the syenites at the east end of Gunflint Lake there is nothing to be seen of any beds representing the tilted slates. The syenites and their associated schists come on at once. (*b*) Where the tilted slates and the conglomerates associated with them are traceable from the syenite upward to the gabbro, as south of Ogishkie Muncie Lake, there is nothing to be seen of any beds like the horizontal black slates of No. 1. (*c*) The "Gunflint beds" appear to belong to the horizontal slates of the international boundary at Gunflint Lake, but their supposed equivalents at Ogishkie Muncie Lake belong to schistose and tilted slates and conglomerate. (*d*) Although the horizontal slates and quartzites of the international boundary strike west and southwest across the State, forming one of the most important topographical features of the northern part of the State, and can be followed for many miles as such, yet they are lost entirely in the region of the upper St. Louis, and the tilted slates are the only ones seen where that river cuts the rock at Knife Falls and below. (*e*) The great gabbro belt which surmounts the horizontal slates along the international boundary, and prevails to the east and south of their line of strike, is seen to pass to the west of Lake Superior at Duluth, and to disappear from sight suddenly between Duluth and Fond du Lac as if its continuance depended on the maintenance of the horizontal formation with which it is associated. (*f*) Where the Gunflint beds become a jaspery hematite, as south and east of Vermilion Lake, the structure of the tilted slates passes into the iron ore as if of the same formation [p. 95].

1883.

Irving, R. D. The copper-bearing rocks of Lake Superior.: Mon. U. S. Geol. Survey Vol. V, 1883, 464 pp., 15 l., 29 pl. and maps. See also Third Ann. Rept. U. S. Geol. Survey, 1883, pp. 89–188, 15 pl. and maps; Science, Vol. I, 1883, pp. 140, 359, and 422; and Am. Jour. Sci., 3d ser., Vol. XXVIII, 1884, p. 462, Vol. XXIX, 1885, pp. 67–68, 258–259, 339–340.

In the above Irving gives a detailed account of the copper-bearing rocks of Lake Superior, and also discusses the relations of this series to the rocks of other ages with which it is associated, and gives many details concerning the associated rocks. The Copper-bearing series does not include the so-called Lower group of Logan, the Animikie group of Hunt, and also the horizontal sandstones known as the Eastern and Western sandstones; although it includes the dolomitic sandstones, with accompanying crystalline rocks occurring between Black and Thunder bays, in the valleys of the Black Sturgeon and Nipigon rivers, and about Lake Nipigon. The Keweenaw or Copper-bearing series then includes the succession of interbedded traps, amygdaloids, felsitic porphyries, porphyry-conglomerates, sandstones, and the conformable overlying sandstone typically developed in the region of Keweenaw Point and Portage Lake. These rocks have their most widespread extent about the western half of Lake Superior, but also occur in the eastern part of the lake. Their entire geographic extent in the immediate basin of Lake Superior is about 41,000 square miles.

The Animikie series in the Thunder Bay district is of great thickness, probably upward of 10,000 feet, comprising quartzites, quartz-slates, clay slates, magnetitic quartzites, sandstones, thin limestone beds, and beds of cherty and jaspery material. With these are associated in great volume, in both interbedded and intersecting masses, coarse gabbro and fine-grained diabase, like those well known in the Keweenaw series. A broad examination of the region shows that there is little ground for the belief in one crowning overflow. The Animikie series is lithologically like the Penokee series in Wisconsin; both series bear the same relations to the newer Keweenawan rocks and the older gneisses, and the two groups are regarded as the same.

The Animikie rocks have been traced by Bell and also by N. H. Winchell as far west as Gunflint Lake, and are the equivalent of, if not actually continuous with, the Mesabi iron range running to Pokegama Falls and the slates of St. Louis River, although the latter are affected by slaty cleavage.

The iron-bearing schists of Vermilion Lake are so like the Huronian that they are regarded as a folded continuation of the Animikie beds, and a generalized section showing the supposed original connection of the Animikie group and the Vermilion Lake iron-bearing schists over the granite of the Mesabi range is introduced.

That the Animikie Huronian is beneath the Keweenawan rocks is shown by the fact that the Keweenawan beds along the Minnesota coast are passed in descending order until the Animikie slates are reached at Grand Portage Bay, but there is not a direct downward continuation of the Keweenawan into the Animikie, for between the two there has been an intervening period of erosion. This is shown by the fact that at Grand Portage Bay, where the two formations come together, the underlying slates suddenly rise entirely across the horizon of 600 or 700 feet of the Keweenawan sandstone. Also in northeastern Minnesota and in the Penokee district the overlying Keweenawan is now in contact with one member of the underlying series and now with another. Further, in the Keweenawan sandstones of Thunder Bay are found chert and jasper pebbles from the Animikie, while in the Wisconsin Keweenawan are quartzite pebbles apparently from the underlying Huronian.

1884.

CHESTER, A. H. The iron region of northern Minnesota: Eleventh Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1882, 1884, pp. 154–167.

This report gives in detail the result of two expeditions sent out, the one in 1878, the other in 1880, by private parties for the purpose of exploring the reported iron-ore deposits in the Mesabi iron range and on Vermilion Lake. The earlier of these two expeditions paid little attention to the Vermilion Lake deposits, and the following facts were obtained chiefly as the result of the expedition in 1880.

The prevailing rocks in the Vermilion Lake iron district are the slates and schists and mica-schists and quartzite found in other Huronian areas in connection with iron-ore beds. The belt of iron ore is well defined. The ore is found in connection with jasper and quartzite, and in many cases with well-defined walls of slate. The ore deposits are intimately bedded with the rocks of the country, slates, schists, and mica-schists and quartzite, and stand nearly vertical, with perhaps a slight inclination to the south, and trend generally east and west, though this varies from place to place. The strata are much folded and contorted (p. 161).

Exploration developed what seemed to be two principal deposits of ore, running nearly east and west, and about a mile apart. The more northern one, nearest the lake, has a total length of nearly a mile, lying in secs. 28 and 27, T. 62 N., R. 15 W. (p. 162).

WINCHELL, N. H. Note on the age of the rocks of the Mesabi and Vermilion iron district: Eleventh Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1882, pp. 168–170.

In this report the general succession of rocks in northeastern Minnesota is given in descending order, as follows: (1) Potsdam, including the Keweenawan sandstones, shales, and conglomerates, changed by igneous gabbros and dolerites locally to red quartzites, felsites, quartz-porphyries, and red granites; (2) Taconic group, including the Animikie series, the Gunflint beds, the Mesabi iron rocks, the Ogishke Muncie conglomerate (?), the Thompson slates and quartzites, and the Vermilion iron rocks; (3) Huronian group (?), including magnesian soft schists, becoming syenitic and porphyritic, found on the north side of Gunflint Lake, along the international boundary, at Basswood Lake, and at Vermilion Lake; (4) Montalban (?), including mica-schists and micaceous granites at the outlet of Vermilion Lake and on the Mississippi; (5) Laurentian, including massive hornblende-gneiss and probably the Watab and St. Cloud granites.

1885.

WINCHELL, N. H. Notes of a trip across the Mesabi range to Vermilion Lake: Thirteenth Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1884, 1885, pp. 20–38.

As the result of a trip from Two Harbors to Vermilion Lake, Winchell finds between these two points two rock ranges, the first being the Mesabi proper, and the second the Giants range. Resting unconformably upon the syenites of the Giants range are the Huronian conglomerates and greenstones of Vermilion Lake, while south of this range are the slates and quartzites of the Animikie, overlain by the gabbro and red granite of the Mesabi range, which is in turn overlain by the trap rocks of the Cupriferous series. The Huronian is considered as resting conformably below the Animikie, although not appearing at the surface. There are three iron-ore horizons—the titanic iron of the gabbro belt, the iron ore of the Mesabi range belonging in the Animikie, and the hematite of the Vermilion mines, which seems to be the equivalent of the Marquette and Menominee iron ores.

Several pages (pp. 25–35) are devoted to a description of the deposits exposed by the stripping operations of the various mining companies, and to analyses of the ore.

A few details are also given concerning the distribution and subdivision of the crystalline rocks of Minnesota (pp. 36–38), from which we learn, in addition to the facts already presented above, that below No. 1 the slates and quartzites of the Animikie lie:

(2) Soft greenish slaty schists, which hold lenticular masses of light-colored protogine gneiss, and also beds of diorite. The horizon of the Vermilion iron mines is thought to be near the bottom of this subdivision or at the top of the next, but on the opposite side of a Laurentian axis, dipping north, and that of the Mesabi iron range, in the foregoing subdivision, dipping south. (3) Conglomeritic and quartzitic slates, which become fine, arenaceous quartzites, and also embrace beds of siliceous marble.

Still further north [lie the gneiss and syenite], accepted . . . as the Laurentian. [pp. 37-38.]

Winchell, N. H. The crystalline rocks of the Northwest: Proc. Am. Assoc. Adv. Sci., Thirty-third Meeting, pp. 363–379. Reprinted in Thirteenth Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1884, 1885, pp. 124–140.

In this paper Winchell divides the rocks of the Northwest into six groups. These groups, in descending order, are as follows, the rocks of the Vermilion range being assigned to Nos. 4, 5, and 6: (1) Granite and gneiss with gabbro; (2) mica-schist; (3) carbonaceous and arenaceous black slates and black mica-schists; (4) hydromica and magnesian schists, the iron-bearing horizon at Vermilion Lake; (5) gray quartzite and marble, which in Minnesota seems to run along the south side of Ogishkie Muncie Lake, near the international boundary, including, perhaps, the great slate-conglomerate which is there represented; (6) granite and syenite with hornblendic schists. This lowest recognized horizon has frequently been styled Laurentian. In Minnesota it is found on the international boundary at Saganaga Lake, and large bowlders from it are included in the overlying conglomerate at Ogishkie Muncie Lake, showing an important break in the stratigraphy.

Van Hise, C. R. Enlargements of hornblende fragments: Am. Jour. Sci., 3d ser., Vol. XXX, 1885, pp. 231–235.

Van Hise describes some enlargements of hornblende fragments and crystals seen in the Ogishke Muncie conglomerate as developed on Kekekabic Lake. A brief description of the macroscopic appearance of the conglomerate, taken from W. M. Chauvenet's notes, is also given.

Irving, R. D. Preliminary paper on an investigation of the Archean formations of the Northwestern States: Fifth Ann. Rept. U. S. Geol. Survey, 1885, pp. 175–242, 10 pls.

In this paper, published in 1885, Irving gives a preliminary account of an investigation of the Archean formations of the Northwestern States.

The problems to be solved in each region are briefly discussed. Here reference will be made only to discussions of rocks occurring in the district described in the present paper.

It is maintained that the series of rocks first called Animikie by Hunt belongs below the Keweenawan rocks. These rocks are presumed to continue with interruptions from Thunder Bay along the boundary to Gunflint Lake, and thence southwest to Pokegama Falls on the Mississippi. Throughout a considerable part of its extent the Animikie series of rocks is bordered on the north by a belt of granite and gneiss, forming the Giants range, to the north of which again come the strongly folded schists of the Vermilion district proper. The main question to be determined here is what the relations of the Animikie to the schists may be. The hypothesis is advanced that they were probably originally connected over the intervening granite range, and are thus really a unit, which as the result of erosion has been separated.

Most of the rocks occurring in the region are sedimentaries that have been indurated by metasomatic action. With these are associated eruptives, some of which have been so modified as to become schists. The cherty and jaspery rocks are supposed to be some sort of original chemical sediment, certainly not, however, the result of metamorphism of ordinary sedimentary material.

1886.

Irving, R. D. Origin of the ferruginous schists and iron ores of the Lake Superior region: Am. Jour. Sci., 3d ser., Vol. XXXII, 1886, pp. 255–272.

In this paper Irving discusses the origin of the ferruginous schists and iron ores of the Lake Superior region. An examination of the Animikie, Penokee, Marquette, Menominee, and Vermilion districts reveals the fact that in all of them is found abundant carbonate of iron, which oftentimes grades into the other forms of the iron-bearing formation. The silica of the jasper, actinolite, magnetite-schists, and other forms of the iron belt never show any evidence of fragmental origin, so easily discovered in the case of the ordinary quartzites and graywackes, and is presumed to be of chemical origin. Associated with the iron-bearing beds is often a considerable quantity of carbonaceous or graphitic schists. It is concluded, (1) that the original form of the iron-bearing beds of the Lake Superior region was that of a series of thinly bedded carbonates, interstratified with carbonaceous shaly layers in places, which were more or less highly ferriferous; (2) that by a process of silicification these carbonate-bearing layers were transformed into the various kinds of ferruginous rocks now met with; (3) that the iron thus removed from the rock at the time of silicification passed into solution in the percolating waters, was redeposited in various places, and thus formed the ore bodies and bands of pure oxide of iron; (4) that in other places, instead of leaching out, the iron has united with the silicifying waters to form the silicates now found, such as actinolite; (5) that the silicifying process went on partly before the folding, partly afterward, and to the latter period belong probably the larger bodies of crystalline ore.

Willis, Bailey. Report of a trip on the Upper Mississippi and to Vermilion Lake: Tenth Census Report, Vol. XV, 1886, pp. 457–467.

Willis, in 1886, describes the rocks and the structure of a small part of the Vermilion district. The area surveyed lies along the south shore of Vermilion Lake, in T. 62 N., R. 15 W., and comprises about 8 square miles. One month was devoted to the study of this, and although for the greater part of the time work was done on snowshoes, many details were carefully noted. Traverses were made one-eighth of a mile apart, and observations for magnetic variation and dip were taken.

The prominent topographic features are described as approximately east and west trending anticlinal ridges of hard jasper, separated by synclinal valleys, in which lie the younger and softer rocks. The north main ridge or group of ridges is known as the Vermilion range. Southwest of this, and separated from it by a valley three-fourths of a mile wide, extends the Two Rivers range. Southeast of the Vermilion range lies Chester Peak (this is now known as Jasper Peak), the west end of the third ridge. The iron-bearing series has a dip of between 85° and 90°. The succession from the base upwards is as follows: (1) Light-green, thinly laminated, chloritic schist. (2) White, gray, brown, and bright-red jasper, interstratified with layers of hard blue specular ore, which also occurs in ore bodies of considerable superficial extent, running across the bedding; thickness 200 to 600 feet or more. (3) Chloritic schist, similar to 1; original thickness probably about 150 feet. (4) Quartzite, dark gray, white, or black, of saccharoidal texture, containing grains of magnetite which make it a readily recognized magnetic formation; probable thickness 200 feet. (5) Conglomerate, consisting of sandstone pebbles and traces of black slate inclosed in siliceous chloritic schist. (6) Compact homogeneous rock, composed of quartz grains, chlorite, hornblende, plagioclase feldspar, and calcite. This rock may be an eruptive quartz-diorite, but is considered a metamorphosed sedimentary transition bed between 5 and 7. (7) Black clay slate, fissile and sonorous. It occupies a broad area north of Vermilion range. In section 28 huge masses of jasper form the crown of the arch and are embedded in green schist, with which they agree in strike and dip. The jasper blocks are rectangular and several hundred feet long; the ends of the bands come out squarely to the contact with the schist as to a fault

1887.

Irving, R. D. Is there a Huronian group?: Am. Jour. Sci., 3d. ser., Vol. XXXIV, 1887, pp. 204–216, 249–263, 365–374.

In these papers Irving discusses the separability of a Huronian group from an underlying series and demonstrates the possibility of such separation in the original Huronian region, in the Marquette and Menominee districts of Michigan, in the Penokee district of Wisconsin and Michigan, and finally in the Vermilion Lake region of Minnesota and Canada (Ontario). In the Vermilion region the gently tilted Animikie series of slates, graywackes, and iron-bearing rocks, with interstratified sheets of diabase and gabbro, resembles very strongly in lithologic aspect the Penokee series of the south shore and rests in palpable unconformity upon a folded series of schists, granites, and gneisses. Above it is the Keweenaw series, which bears the same unconformable relations to the underlying rocks as it does to the Penokee series.

Thus the Animiké series occupies very plainly the stratigraphical position of the original Huronian and of the various iron-bearing groups of the south shore of Lake Superior. Since it is also intrinsically so extraordinarily like the Penokee series as to leave no doubt of their identity, and since the Penokee is as evidently the equivalent of the original Huronian, we seem to be left no choice as to calling the Animiké Huronian also [p. 263].

North of the Animikie beds are schistose iron-bearing rocks, which extend from Vermilion Lake to the vicinity of Knife and Saganaga lakes. These are flanked by gneisses and granites, and on account of their lithologic similarity to the Animikie rocks are taken to be their folded equivalent. While there is not here the same palpable unconformities as in the other regions discussed, it is believed that there are two groups of rocks, one of crystalline schists, and another of newer detrital rocks, the apparent unconformity between these being due to the intense folding.

WINCHELL, A. Report of geological observations made in northeastern Minnesota during the season of 1886: Fifteenth Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1886, 1887, pp. 5–207.

In this report are given the detailed observations made on an extensive trip in northeastern Minnesota.

The region presents a series of schists flanked on the north and south by massive crystalline rocks. In the western part of the district these rocks are gneissic on both sides, but in the eastern part the schists extend on the north beyond the limits of the map, while on the south the gneissic rocks are replaced by gabbro and greenstone. The schists and bedded crystallines stand in nearly vertical attitude.

It is said that the indications of a genetic connection between graywacke and the mica-schists are very noteworthy, a gradation from one to the other having been noted in numerous instances (p. 176). Likewise the schists grade into the gneissic rocks, there being nowhere an abrupt passage from one class to the other. In the passage from the schists to the gneisses there is, first, an increase in frequency of ramifying veins, next, lumps of gneiss or granite occur in the schists, and finally there is interstratification of the schists and gneisses (p. 178). The author expresses himself (p. 179) as uncertain whether or not the conglomerate at Ogishkie Muncie Lake, which attains an enormous development and contains varieties of granitic and quartzose bowlders, as well as flint, jasper, porphyry, and greenstone, exists as far west as Vermilion Lake; however, there is apparently no doubt that it lies in the strike of the schists occurring at the west end of the range on Vermilion Lake. It thus seems to be a local development of the schists. The beds of bowlders are interbedded with flinty argillites, which attain their greatest development north of the conglomerates; the southern border of the conglomerates is concealed by overlying greenstone and gabbro. Some sericitic beds have been discovered within the conglomerate formation. These facts lead the author to conclude that the conglomerate belongs in stratigraphic position within the northern border of the sericitic schists, and the southern border of the argillites as they appear farther west. The entire system of gneisses, schists, and slates is regarded as belonging to one structural system, as they all possess a common dip and pass by gradations into each other, both along the strike and across it (p. 181). The iron-bearing rocks are interlaminated with the country schists, and while they exhibit much persistence in the direction of the strike, they do not continue without interruption; they appear in the midst of the schists sometimes as a strictly local phenomenon (p. 182). In structure the region is a simple synclinical fold, the strata of which have a thickness of 106,204 feet. The succession, from the bottom upward, is granite, gneiss, micaceous and hornblendic schists, graywacke, argillite-schist bearing conglomerates, and sericitic and chloritic schists bearing iron ore (p. 191). As the plainly fragmental rocks grade by imperceptible stages into the gneiss and the gneiss into the granite, the whole is regarded as a sedimentary series (p. 193). While granite pebbles are found in the conglomerates, these are not derived from the underlying granite, as many of the fragments differ in character from the inferior granite (p. 194).

The author places the conglomerates stratigraphically below the iron ores and jaspers. He makes the following statement:

> We find flints and jaspers, which, as far as we have explored, could not be afforded by any part of this system. We find nothing which indisputably could have been derived from any member of the system—the Vermilion system—ranging from the granites to the earthy schists. Those older rocks whose destruction afforded material for the building of the Vermilion system belonged to an earlier age, and were parts of an older system [pp. 194–195].

They all belong to one system, for no grounds were discerned which would justify the division of this series of rocks into several systems (p. 195).

WINCHELL, N. H. Geological report: Fifteenth Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1886, 1887, pp. 209–399, with map.

In this report Winchell gives very numerous details as to the geology of northeastern Minnesota. A preliminary geologic map accompanies the report. At several places there are transitions between the granite-gneiss and a fine-grained mica-schist. In the syenite are sometimes found angular fragments of mica-schist. The Vermilion group is defined as including the lower portion of the complex series of schists designated as

Keewatin by Lawson. It embraces the mica-schists and hornblende-schists of Vermilion Lake and their equivalents, and lies between the graywackes on the one side and the basal syenites and granites on the other.

Adjacent to Vermilion Lake are hematite ores associated with jasper, which are inclosed in a greenish magnesian schist, the bedding of which stands vertical. This schistose rock is probably of igneous origin, and in its relations to the jasperoid rocks it fills all their cavities, overlying them unconformably, and holding fragments of the jasper, all indicating its later origin. This igneous rock passes into a chlorite-schist, and this into the sericite-schists and graywackes, which show unmistakable evidence of an aqueous arrangement (pp. 219-221). The jasperoid is a sedimentary rock (p. 245 et seq.) and not an eruptive, as has been supposed by Wadsworth. The rock was not, however, deposited in its present condition. The beds have been upturned, folded, crushed, and affected by intense chemical action. The ore is regarded as a result of chemical or metasomatic change. The ore is a hard hematite and of such good quality as to warrant a guarantee of 67 per cent or more of iron, and 0.06 per cent or less of phosphorus. The general succession from above downward is as follows: (1) Gabbro. (2) Diabasic dolerite. These rest unconformably upon the lower members. (3) Reddish gneiss and syenite, which includes the Misquah Hills, White Iron Lake and the Giants range (Mesabi heights). This is a case of a fusion of sedimentary beds in situ, although it is not generally complete. (4) Graywacke, sericite-schist, argillite, quartzite, and jaspilite, which occur about Vermilion Lake. (5) Mica-schist, hornblende-schist, and diorite—the Vermilion group. (6) Mica-schist and granite, veined with syenite and granulite. (7) Lower syenites and gneisses, generally regarded as Laurentian. Nos. 3 to 7 are conformable, and Nos. 4 to 7 graduate into each other (p. 355).

The author states it as his opinion (p. 356) that there is reason for believing that the Animikie rocks overlie the greenstone (No. 2) and underlie the gabbro (No. 1) of the above succession.

1888.

Winchell, N. H. Sixteenth Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1887. 1888. pp. 13–129.

Winchell, as customary, publishes in the annual report his field notes for the preceding year, giving an abundance of details about the rocks of the Vermilion district. As a result of a traverse made into Canadian territory from the east end of Gunflint Lake, he comes to the conclusion that the Animikie, on Gunflint Lake, while not found in exact superposition on the Keewatin, bears such relation as to render it probable that the two formations are discordant. A short distance north of the Animikie the Keewatin rocks are found with a dip of 80° south, and these, a little farther to the north, grade conformably into micaceous and hornblendic schists. He continues as follows:

In the report of 1881, p. 95, . . . some reasons are given for considering the "quartzite-slate formation" seen at Gunflint Lake (the Animike) in horizontal position, the equivalent of the great quartzite and slate formation at Ogishke Muncie Lake, which passes into the Ogishke conglomerate. . . . At that time the tilted schists and graywackes of the Kewatin series, with their contained iron ore, were considered an integral part of the same tilted series as the slates and quartzites associated conformably with the Ogishke conglomerate, and the iron ore of the jasper ridges at Vermilion Lake were considered the equivalent of the iron ore seen in the Animike. . . . But since the separation of the Animike from the Kewatin has been established by marked unconformities, and by constant differences in lithology (including a constant difference in the kind of iron ore associated and their respective mineral accompaniments), it remained still to answer the question, To which series, the Animike or the Kewatin, does the quartzite-slate conglomerate of Ogishke Muncie Lake belong? [p. 79.]

An attempt was made to trace the Animikie westward and get its relations to the rocks on Ogishke Muncie Lake. The Animikie rocks rest unconformably on the gneiss west of Gunflint Lake. The Pewabic quartzite is a magnetited rock apparently near the top of the Animikie. The gabbro is observed overlying the Animikie (Pewabic quartzite) at many places. The Animikie lies unconformably on the Keewatin north of Gunflint Lake (p. 87). In passing from Gunflint Lake the Animikie is found to have a dip varying from 12° to 55° SSE. At Gabemichigama Lake a gradation is supposed to exist from the flat-lying Animikie into the Ogishke Muncie conglomerate, with interstratified quartzite and slate beds striking northwest and dipping 88° northeast (p. 91).

Studies made around Ogishke Muncie Lake show that the Ogishke conglomerate can be divided into, first, an old, eruptive-looking, massive schistose and decayed conglomerate, which belongs to the Keewatin, and extends from Stuntz Island, in Vermilion Lake, past Ely (where it was recently examined at the iron mines) to Twin Mountain and Frog Rock Lake; second, the Ogishkie conglomerate proper of later date, fresher aspect, and more siliceous, evidently derived largely from the disintegration of the other, upon which it lies unconformably. With this second phase the Animikie quartzite and slates are interstratified (p. 98).

Partly surrounding Cacaquabic Lake is found a green schist which belongs apparently to a date about the same as the Keewatin portion of the Ogishke conglomerate or is its immediate successor and conformable upon it. Nevertheless they are markedly different. The green schist is apparently formed of basic erupted materials in a fragmental condition and received its stratified arrangement through the agency of water. Volcanic vents in the immediate neighborhood must have given origin to this vast supply of basic materials (p. 108).

It is concluded that a great basic eruption separated the Animikie and Keewatin, as shown by this volcanic fragmental material, as well as by the existence of mountains of greenstone, which are to be regarded as the probable sources of the fragmental rock (p. 108).

Winchell, A. Sixteenth Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1887, 1888, pp. 133–391. Unconformability between the Animikie and the Vermilion series: Am. Jour. Sci., 3d ser., Vol. XXXIV, 1887, p. 314. See also: The unconformities of the Animikie in Minnesota: Am. Geologist, Vol. I, 1888. pp. 14–24. Two systems confounded in the Huronian: Am. Geologist, Vol. III, 1889, pp. 212–214, 339–340. Systematic results of a field study of the Archean rocks of the Northwest: Proc. Am. Assoc. Adv. Sci., Thirty-seventh Meeting, 1888, pp. 205–206. The geological position of the Ogishkie conglomerate: Proc. Am. Assoc. Adv. Sci., Thirty-eighth Meeting, 1889, pp. 234–235.

In the above papers Alexander Winchell reports that he finds upon Wonder Island, in Lake Saganaga, a conglomerate which contains abundant rounded pebbles in a groundmass of syenite (p. 219). This occurrence gives rise to the following suggestion in the author's mind:

The inferences from the occurrence are important. A pudding stone like this is universally regarded as of fragmental origin. Not only that, but of origin through aqueous agency. . . . So, if this conglomerate is sedimentary in nature, the syenite groundmass must, at the time of the deposition of the pebbles, have been also in a state of semifluidity under the influence of water. It may have been subjected simultaneously to energetic thermal action; but it was not in that state of fluidity which accompanies and results from recent eruption as molten matter from some deep source. This view of the origin of granitic rocks I have heretofore maintained, and this remarkable observation is a gratifying confirmation of the correctness of the opinion [p. 219].

The lower limit of the conglomerate is very abrupt, and the conglomerate is figured as overlying the syenite. Nevertheless it is concluded that—

The epoch of the paste [in which the pebbles lie] and that of the deposition were the same. The conglomerate and the syenite were put in place simultaneously. The syenite was not "erupted" after the conglomerate existed. The conglomerate was not laid down on the solidified syenite [p. 221].

On the north side of Gunflint Lake he finds argillites standing nearly vertical.

They are not at all ambiguous. They are the Knife Lake slates preserving to this point their steady verticality, and here remaining uncovered by Animike. This looks like a solution of a vexed problem. The Animike and the Vermilion slates *are not one* . . . The dip [of these slates] is S. 89°. The strike of the sheet is N. 72° E. [p. 253].

The Animikie slates are found resting unconformably upon vertical schists, gneisses, and syenites at several points on Gunflint Lake [p. 323]. On the west side of West Sea Gull Lake the conglomerate and syenite are reported as interbedded. This conglomerate is thought to be comparable with that of Wonder Island (p. 293). On the north side of Sea Gull Lake the syenite contains sharply limited rounded pebbles and irregular masses of hornblendic and diabasic material (p. 298). On Epsilon Lake the argillite has schistic planes standing vertical, while the bedded structure has a dip of only 23° toward S. 40° W. (p. 322).

From the summary of facts concerning the region we learn:

Within the region here considered the geographical distribution of the several terranes is east-northeast in the Vermilion district and nearly east in the district eastward from Knife Lake. Throughout the entire region the clastic rocks—not excluding the so-called granites and syenites, present a bedded structure—sometimes indeed obscure, but everywhere discernible over all considerable exposures. Among the granites and gneisses the bedding may possibly be regarded as the result of foliation alone; but I have been led to think that its direction was predetermined by planes of sedimentation. . . . For similar reasons, I regard the bedding of the crystalline schists as primitively sedimentary. The two older systems of rocks have their planes of bedding nearly vertical—inclining only a few degrees in one direction or the other. The bedding of the newer system is nearly horizontal—inclining five to fifteen degrees southward in the regions here reported on [p. 330].

Summing up, we get the following succession (pp. 330–364):

1. At the base are the *granitoid* and *gneissoid* rocks in three areas—the Basswood, White Iron, and Saganaga lakes. The White Iron granite area is made to include the area on and near Snowbank Lake that is underlain by granite. These granitic masses have everywhere a bedded structure, more or less distinct. They are traversed by quartzose and granulitic veins, as well as by dikes of diabase.

2. The gneisses and granites are flanked by vertical *crystalline schists of the Vermilion group*. The transition from the gneisses to the crystalline schists is never abrupt, but is a structural gradation, near the line of junction the beds of gneisses and schists occurring in many alternations.

3. Above the Vermilion group are the *Kewatin semicrystalline schists*, the two series being everywhere conformable; but there is a somewhat abrupt change from one group to the other, and this indicates the possibility of an original unconformity. If such an unconformity existed, as is thought improbable, it has been destroyed by laterial pressure. There has been no actual connection traced between the Kewatin schists north of Gunflint Lake and those of Knife Lake. The Kewatin schists are almost everywhere vertically bedded. When the bedding is obscure this is sometimes due to the action of erupted masses, but more often the metamorphosed condition of the strata is not ascribable to any visible cause. The Kewatin schists include graywacke, argillite, sericite-schist, chlorite-schist, porphyrellite-schist, and hematite. The Ogishke conglomerate is placed as part of the Kewatin system, as it is traced by actual gradations into the adjoining argillites. These argillites and associated schists are in continuity with the argillites and schists of Vermilion Lake, while in the conglomerate itself are local developments of sericite-schist. The bedding of the conglomerate is nearly vertical; its pebbles are metamorphosed; they include numerous varieties, among which are syenite resembling the Saganaga syenite, greenstone, porphyry, red jasper, flint, quartz, petrosilex, ordinary syenite, diorite (coarse and fine), porphyroid, siliceous schist, and carbonaceous siliceous argillite. On structural as well as lithologic grounds the Ogishke conglomerate seems to be part of the Kewatin, although there are some reasons for suspecting it to belong to the Animikie.

The Ogishke conglomerate is not to be confounded with the Stuntz conglomerate, which occupies a lower stratigraphic position than does the Ogishke. That the Kewatin schists are eruptive is regarded as improbable.

4. The Animikie series, resting unconformably upon the Keewatin, stretches from Thunder Bay as far as Duluth and still beyond to the Mississippi, and perhaps includes some of the slates as far west and north as Knife Lake. The Animikie formation is generally in a nearly horizontal position, the dip not being more than from 5° to 15° SSE. The formation is essentially an argillite, which embraces jaspery magnetitic, hematitic, and sideritic beds. At Gabimichigama Lake the Animikie, represented by the "muscovado," is in its characteristic horizontal position, while the vertically bedded terrane underlies it. The sedimentary series is cut by dikes of igneous rock, determined macroscopically as diabase-norite and porphyry.

For the system of semicrystalline schists subjacent to the Animikie, to which the term Kewatin has been applied, Marquettian is proposed. The succession of terranes in northeastern Minnesota is, in descending order, summarized as follows (pp. 366–367):

HURONIAN SYSTEM (compare sec. 2 of this report[a]), over 4,082 feet.
- Magnetitic group. 32 feet.
  - Dark, laminated, shaly argillite, sometimes magnetitic, 29 feet.
  - Magnetitic beds, often uppermost, 8 feet. Place of sideritic bed?
  - Muscovado, uppermost when the two above are wanting, 4 feet.
- Siliceous group. 50 feet.
  - Siliceous argillites and siliceous and jaspery schists, 50 feet.
- Argillitic group. 4,000 feet.
  - Dark, laminated, shaly argillites, over 4,000 feet in Minnesota.
  - (Bottom of the system not reached at contacts seen with gneiss and Marquettian.)

MARQUETTIAN SYSTEM. 27,500 feet.
- Ogishke group. 10,000 feet, but local. (Perhaps half this).
  - Ogishke conglomerate, slaty and diabasic. 4,500 feet each side of synclinal.
  - Ogishke dolomite, included in the conglomerate, 10 feet.
  - Conglomerate greenrock. 500 feet each side of synclinal.
- Tower group. (Earthy schists.) 15,000 feet.
  - Sericitic and argillitic schists, with beds of hematite, 5,000 feet.
  - (These sometimes changed to chloritic schists.)

[a] This refers to Sixteenth Ann. Rept. Minn. Geol. and Nat. Hist. Survey.

MARQUETTIAN SYSTEM—Continued.

Tower group—Continued.

(They pass eastward into schists prevailingly porphyrellitic.)

Stuntz conglomerate, porodyte and porphyrel, 20 feet.

Graywacke group. 2,500 feet.

Graywacke and hornfels.

Graywacke with indications of fine mica and hornblende. ("Nascent mica schists.")

LAURENTIAN SYSTEM. 89,500 feet.

Vermilion group. Over 1,500 feet.

Crystalline schists—micaceous, hornblendic, dioritic, granulitic.

Gneissic group. Over 88,000 feet.

Chlorite-gneiss. (Not universally developed.)

Saganaga, White Iron, and Basswood gneisses.

Thus the crystalline schists and gneisses fall entirely within the Laurentian system. There are no Huronian gneisses in Minnesota. We find nothing of "older" and "newer" gneisses. We find no "clay slates" beneath the horizon of the crystalline schists. But I can not deny the existence of a different state of things in other regions. To me it seems probable, however, that a comparatively undisturbed region like northeastern Minnesota must approach near to a normal exhibit of the real succession of the Archean rocks.

IRVING, R. D. On the classification of the early Cambrian and pre-Cambrian formations: Seventh Ann. Rept. U. S. Geol. Survey, 1888, pp. 365–454, with 22 plates and maps.

Irving, in 1888, discusses the classification of the early Cambrian and pre-Cambrian formations, and particularly those of the Northwestern States. The relations of the Animikie, Penokee, Marquette, Menominee, and Vermilion Lake iron-bearing series to the underlying and overlying series are again fully discussed. The Keweenawan is held to overlie the Huronian everywhere by a very considerable unconformity. At the base of the Keweenawan is a great mass of gabbro, which extends from Duluth northeast to the international boundary, more than 100 miles, and at its maximum is more than 20 miles wide. This basal gabbro is now in contact with one member of the Animikie, and now with another, while in other places it is in contact with the lower crystalline schists or granite. In the Huronian are placed the original Huronian, the Iron-bearing series of Michigan and Wisconsin, the Black River Falls iron-bearing series, the Animikie series, the St. Louis and Mississippi slate series, the Vermilion Lake iron-bearing series, the Baraboo quartzite series, and the Sioux quartzite series. Under the Huronian is the Laurentian, separated from it by a great unconformity. This is a series of granites, gneisses, hornblende-schists, mica-schists, and other green schists.

1889.

HALL, C. W. The distribution of the granites of the Northwestern States, and their general lithologic characters: Proc. Am. Assoc. Adv. Sci., Thirty-seventh Meeting, 1889, pp. 225–226.

In the above paper Hall describes the distribution of the granites of the Northwestern States, particularly those of Minnesota.

In Minnesota they occur (1) in several belts along the Canadian boundary projecting southwesterly into the State; (2) as quite prominent masses, whether connected with those along the boundary or not, around Vermilion, Snowbank, and other lakes; (3) forming the Mesabi or Giant range; (4) at a number of places in the central part of the State. These are found to be either intrusive or granitic vein-stones, the latter being insignificant in quantity. The granites of Minnesota as to age are probably later than the Laurentian floor of the continent, but earlier than those of the Agnotozoic era.

They belong to one of the three or four grand periods of eruptive activity determinable in the Northwestern States.

WINCHELL, N. H. Seventeenth Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1888, 1889, pp. 5–74; see also the Animikie black slates and quartzites, and the Ogishki conglomerate of Minnesota, the equivalent of the "Original Huronian:" Am. Geologist, Vol. I, 1888, pp. 11–14; also Methods of stratigraphy in studying the Huronian: Am. Geologist, Vol. IV, 1889, pp. 342–357.

In this, Winchell gives a review of the work done upon the crystalline rocks of northeastern Minnesota by the State survey, showing the progression in the ideas held concerning their characters and stratigraphy (pp. 6–28). Then follows a summary of the results of the investigations as they appear up to that time (pp. 28–74). In many points the conclusions and facts are the same, of course, as in the previous reports. The Laurentian age (pp. 28–31) is made to include the gneiss, granitic, and syenitic, but excludes the crystalline schists. It is the fundamental gneiss of Minnesota. "It resulted from the fusion and recrystallization of the earliest sediments" (p. 28).

The Laurentian gneiss is represented in the Vermilion district by the Basswood Lake and perhaps the Saganaga Lake granite. However:

> There may be spots, or considerable areas, within this original gneissic belt, where, by subsequent deep-seated hydrothermal fusion, these primitive Laurentian sediments have been rendered plastic and then fluid, and have by pressure been extended through fissures in the crust to the surface or have been uncovered as laccolites by the destruction of the overlying strata; but wherever these exist they are presumed to show their later origin by their nongneissic structure, or by their overlying some later sedimentary strata. The distinction, however, between the eruptive condition of the fused Laurentian sediments and the primitive sediments that have been converted in situ into the fundamental gneiss is one that requires more study before it can be defined. That both conditions exist there can be no question; that they can always be distinguished is not to be affirmed [p. 29].

Closely associated with the belts of fundamental gneiss are areas of massive erruptive syenite which have resulted from such hydrothermal fusion of the gneiss. Such syenite is found north of Gunflint Lake, on the shores of Cacaquabic Lake.

The Laurentian gneisses are seen at places to be conformable with, and to grade into the hornblendic and micaceous "crystalline schists"—the Vermilion schists, which are the equivalents of Lawson's Coutchiching. At other places the gneisses and schists are uncomformable and here they both play the rôle of eruptive rocks interpenetrating, in the form of transverse dikes, and inclosing fragments of each other. This relationship is considered to be evidence of volcanic action. "It is manifest, therefore, that the supposition of the advent of a characteristically eruptive era, closing the quiet Laurentian sedimentary age, will account for both an unconformable and a conformable transition, such as are seen, from the Laurentian to the Vermilion" (p. 35).

The Vermilion group passes by conformable transition into the Keewatin. The character of the Keewatin rocks indicates that there was active volcanic action during the whole period, and that the ejectamenta were received and distributed by the waters of the surrounding sea. This is indicated by the alternation of the breccias and volcanic material with truly sedimentary strata. The name Kawishiwin is proposed for the massive greenstone stage of the Keewatin. The Keewatin is the iron-bearing formation. The iron ore is associated with the jaspilite, which is of a sedimentary origin. Above the Keewatin is a profound unconformity (pp. 37–46). Above this lies the Animikie. This has the Ogishke conglomerate as its base.

This conglomerate is followed by an immense thickness of dark slaty rocks, often cherty, or flinty, frequently very dark-colored, generally siliceous, alternating with thin quartzites and grayish feldspathic quartzites, all in conformable stratification, as a whole. Variously interbedded with these slates and quartzites, from bottom to top, are beds of basic eruptive rock, . . . [pp. 47–48].

The Animikie series of Minnesota, bearing iron at one horizon, is the equivalent of the Marquette series, the iron-bearing group of Rominger, of the Penokee-Gogebic series of Michigan and Wisconsin, of the Mesabi series in Minnesota, of the Black River iron-bearing schists in Wisconsin, and of the quartzites of the Black Hills. All are of Taconic age, for the Lower Cambrian is equal to the Taconic, the Huronian is equal to the Taconic, therefore the Lower Cambrian is equal to the Huronian (pp. 46–48).

In the Potsdam sandstone, which is uncomformably on the Taconic, are included the upper quartzites of the original Huronian, certain of the quartzites of Marquette, the Sioux quartzites of Dakota, and the quartzites of Minnesota and Wisconsin. This is also the age of the copper-bearing rocks, which are an alternation of basic and acid eruptions with interbedded sandstones and conglomerates. The great gabbro eruption is later than the beginning of the Potsdam age. Unconformably above the Potsdam is the St. Croix sandstone (pp. 51–57).

The general succession in descending order, is as follows (p. 68):

Calciferous. Magnesian limestones and sandstones.. } ..... Dikelocephalus horizon
St. Croix. Sandstones and shales................... }

Overlap unconformity.

Potsdam. Quartzite, gabbro, red granite, and Keweenawan....Paradoxides horizon

Overlap unconformity.

Taconic. Black and gray slates and quartzites, iron ore (Huronian, Animike)..Olenellus horizon

Overlap unconformity.

Kewatin. (Including the Kawishiwin or greenstone belt, with its jaspilite), sericitic schists and graywackes.................... }
Vermilion. (Coutchiching) crystalline schists.................... } Archean

Eruptive unconformity.

Laurentian. Gneiss.. }

WINCHELL, H. V. Report of field observations made during the season of 1888 in the iron regions of Minnesota: Seventeenth Ann. Rept. Geol. and Nat. Hist. Survey of Minn., for 1888, 1889, pp. 77–145; see also The diabasic schists containing the jaspilite beds of northeastern Minnesota: Am. Geologist, Vol. III, 1889, pp. 18–22.

In the above H. V. Winchell gives further observations on the iron regions of Minnesota. On the Giants range the Animikie is found to rest upon the syenite. There is a semicrystalline rock between the two, which grades into the syenite. The character of the transition is not metamorphic, but rather fragmental, there appearing to be a certain amount of loose crystalline material which has resulted from the decay and erosion of the syenite lying on top of this rock in the bed of the sea, upon and around which the Animikie sediments were deposited. The coarse detritus grades up into the fine detritus of the Animikie (p. 86). The Animikie beds are found also to rest unconformably upon the upturned edges of the Keewatin schists (p. 87). The same relations are found to prevail in the Birch Lake region (p. 91). The gabbro containing ores in the vicinity of Kawishiwi River are found to contain fragments of the Animikie slates and quartzites, and is therefore of later origin (pp. 96–97). At Gunflint Lake the Animikie rests unconformably upon the Keewatin (p. 104). The Keewatin schists are largely of eruptive origin (p. 132). The contacts of the jaspilite with the basic schists are abrupt and angular, and numerous fragments are found contained in the schists. The jaspilite is regarded as a sedimentary formation, which was broken up and involved in the eruptions of Keewatin time. The Huronian quartzite, associated with the magnetite, lying unconformably upon the syenite, is believed to lie conformably upon the Animikie slates (p. 133).

GRANT, ULYSSES S. Report of geological observations made in northeastern Minnesota during the summer of 1888: Seventeenth Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1888, 1889, pp. 147–215.

In this report Grant gives an account of the geologic observations made by him in northeastern Minnesota.

North of Gunflint Lake the vertical Keewatin slates and Vermilion crystalline schists, with an east and west strike, strike directly across a range of immediately adjacent gneisses, the schists showing no evidence of being twisted or bent within 200 feet of the gneiss. In the syenites of Gunflint Lake are found fragments of schist, which indicate that the syenite is eruptive later than the schists (p. 159).

WINCHELL, ALEX. Conglomerates enclosed in gneissic terranes: Am. Geologist, Vol. III, 1889, pp. 153–165, 256–262.

In this paper Alexander Winchell restates his conclusions concerning the origin of the Saganaga (Sixteenth Ann. Rept., p. 219) and Sea-Gull (Sixteenth Ann. Rept., p. 298) syenite conglomerate. He maintains in this paper that the conglomerate is produced from a fragmental rock by selective metamorphism, the completely crystalline gneissoid rocks retaining rounded fragments which are residual clastic material. The conglomerate of Wonder Island is not one consisting originally of a mass of pebbles, over which a fluid magma has been poured, for the pebbles are not in contact; they could not have lain where they are before the magma existed. The gneissic magma was contemporaneous with the pebbles, and supported them and prevented their contact. The magma must have been plastic, but it was low-temperature igneo-aqueous plasticity.

WINCHELL, N. H. Some thoughts on eruptive rocks, with special reference to those of Minnesota: Proc. Am. Assoc. Adv. Sci., Thirty-seventh Meeting, 1889, pp. 212–221.

N. H. Winchell, in 1889, in a general discussion of the origin of the eruptive rocks, maintains that there are four epochs of basic eruption in Minnesota: First, that represented by the crystalline schists of the Vermilion group; second, an epoch succeeding the graywackes of the Keewatin and forming a part of the Keewatin; third, one succeeding the Animikie, during which the Great gabbro or Mesabi overflow was outpoured.

1890.

Report of the Royal Commission on the Mineral Resources of Ontario and Measures for their Development. Toronto, 1890, pp. 123–126.

In this report there is a brief description of observations made by three members of the commission who visited the Vermilion district. No statements of geologic character which are of any interest are given. Statements were gathered from miners and prospectors which show that promising iron-bearing formations exist in Ontario in the northeastern extension of the Vermilion iron range.

WINCHELL, N. H. and H. V. On a possible chemical origin of the iron ores of the Keewatin in Minnesota: Am. Geologist, Vol. IV, 1890, pp. 291–300, 382–386; also Proc. Am. Assoc. Adv. Sci., Thirty-eighth Meeting, 1890, pp. 235–242.

In the above papers N. H. and H. V. Winchell maintain that the iron ores of the Keewatin of Minnesota are not derived from a carbonate, but are probably a direct chemical precipitate; for there is no evidence of the existence of carbonate of iron at any time, and the nature of the country rock is such as to imply that no carbonates in amounts required could have been deposited at the time the rocks were formed.

Winchell, Alexander. Some results of Archæan studies: Bull. Geol. Soc. Am., Vol. I, 1890, pp. 357–394.

Alexander Winchell in 1890 repeats his general conclusions as to the stratigraphy in northeastern Minnesota already given in his reports of field work in the Vermilion district for the years 1886 and 1887, and published in the fifteenth and sixteenth annual reports of the Minnesota survey, pages 5–207 and pages 133–391.

Summed up, these conclusions are briefly as follows: In northeastern Minnesota there are large areas (in the Vermilion district four) of granitoid and gneissoid rocks which have oval outlines trending in general northeast-southwest. Gneissoid rocks predominate, and the rocks approaching a granitoid condition are found only at the centers of the areas. These gneissoid areas are surrounded by crystalline schists, mica-schists, hornblende-schists, or mica-hornblende-schists, known as the Vermilion series. These strike east-northeast. The dip increases away from the granitoid areas until it becomes vertical. The gneissoid (granitoid) rocks and schists are intimately connected, and the author, while declining to make a definite statement, clearly intimates that the gneiss, granites, and schists are all of sedimentary origin. Referring to those rocks, he says:

> They are so inseparable on any fundamental grounds, and are so blended together, both structurally and mineralogically, that no reasons appear to exist for a reference of one class to a mode of origin fundamentally different from the mode of origin of the other class. On this question, however, I only propose at present to cite some observed facts. The interpretation of them may be subsequently undertaken.
>
> The crystalline schists are succeeded by a system of semicrystalline schists [the Keewatin]. They range, however, from fragmental crystalline to earthy. They succeed in perfect structural conformity with the older schists, with only slight indications of stratigraphic disturbance. Their attitude is generally vertical or steeply inclined. Their position is between and surrounding the gneissoid areas [p. 377].

In the Vermilion district, as they lie between two elongated gneissoid areas, they have a persistent east-northeast strike for 70 miles. In each of the intervals between such gneissoid areas the semicrystalline schists prevent the structure of a simple synclinal fold. Petrographically the semicrystalline schists (Keewatin) are sericitic schists inclosing beds of hematite, argillite, including the Ogishke-Muncie conglomerate, porphyrellite and chloritic schists, porodites, agglomerates and tuffs, and graywackes.

Wherever the crystalline and semicrystalline schists are seen in juxtaposition their stratification is strictly conformable. Wherever the crystalline schists are wanting the semicrystalline schists are found in conformity with the gneisses. Moreover, whether the semicrystalline schists occur in juxtaposition with the crystalline schists or the gneisses, there exist frequently those transitions by alternation which characterize the passage from the crystalline schists to the gneisses. This mode of transition, however, is much the most characteristic of the passage from the semicrystallines to the crystallines [p. 383].

Statement is also made of the petrographic gradation between the semicrystalline and crystalline schists.

The uncrystalline schists (Animikie) are chiefly thin-bedded black argillites grading into graywackes and even into conglomerates, with flint and jasper schist and beds of magnetite. These rocks overlie the semicrystalline Keewatin schists with strong unconformity.

The enumeration made embraces all rocks up to the Keweenawan. So far as these groups are concerned the order, in descending succession, is as follows:

5. The uncrystalline schists (Animikie, Huronian).
4. The semicrystalline schists (Keewatin).
3. The crystalline schists (Vermilion).
2. The gneissoid rocks } (Laurentian).
1. The granitoid rocks }

WINCHELL, N. H. and H. V. The Taconic iron ores of Minnesota and of western New England: Am. Geologist, Vol. VI, 1890, pp. 263-274.

In 1890 N. H. and H. V. Winchell state that the iron ores of Minnesota are, at five different geologic horizons, in descending order, as follows: (1) The hematites and limonites of the Mesabi range, the equivalents of the hematites of the Penokee-Gogebic range in Wisconsin; (2) the gabbro titaniferous magnetites near the bottom of the rocks of the Mesabi range; (3) olivinitic magnetites, just below the gabbro in the basal portion of the Mesabi rocks; (4) the hematites and magnetites of the Vermilion range in the Keewatin formation; (5) the magnetites of the crystalline schists of the Vermilion formation. It is maintained that the upper iron deposits of the Mesabi and those of the Penokee-Gogebic are the equivalents of the Taconic ores of western New England.

Irving, R. D., and Van Hise, C. R. The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey Vol. XIX, 1892, pp. 534, with pls. and maps. See also Tenth Ann. Rept. U. S. Geol. Survey, 1890, pp. 341–507, with 23 pls. and maps.

Irving and Van Hise in 1890 and 1892 give a detailed description of the Penokee series of Michigan and Wisconsin, and of the complex of rocks south of this series. They discuss the relations which the Penokee rocks bear to the underlying and overlying series, as well as to the Eastern sandstone. The Marquette and Felch Mountain series of Michigan, the Menominee series of Michigan and Wisconsin, and the Animikie and Vermilion Lake series of northeastern Minnesota and Ontario are alluded to, since they contain large developments of rocks which are almost exact reproductions of the iron formation rocks in the Penokee series. The Animikie is considered in more detail than the rest, since a comparison of its iron-bearing formation shows that it consists of the same kinds of rocks which have been derived from an iron carbonate in the same manner as those of the iron formation of the Penokee series.

A further comparison of the Penokee series proper and the Animikie series shows that they also occupy the same relative positions with reference to overlying and underlying rocks, one dipping northward under the basin of Lake Superior and the other dipping southward under the same body of water. They are therefore regarded as equivalent. The rocks in various other areas in the Lake Superior basin referred to the Upper Huronian are regarded as probably equivalent with the Penokee series

1891.

Van Hise, C. R. An attempt to harmonize some apparently conflicting views of Lake Superior stratigraphy: Am. Jour. Sci., 3d series, Vol. XLI, 1891, pp. 117–137.

In the above paper Van Hise describes the physical break between a Lower and an Upper Huronian series. That the two series are separated by a great unconformity is shown by numerous contacts. At these contacts the lower quartzite of the Upper series contains abundant fragments of the Lower series which had reached their present condition before being deposited in the former. That the Lower series has been greatly folded and deeply truncated before the Upper series was deposited is further shown by the much banded and contorted jasper abutting at all angles against the beds of the uptilted but simply folded Upper series, and also by its more crystalline character.

Since great belts of conglomerates containing abundant fragments of ore and jasper are found in the Upper Vermilion, at Ogishki Lake, and in the Upper Kaministiquia series, it is argued that the source of this material is the great belts of iron ore and jasper contained in the Lower Vermilion, Hunters Island, and Lower Kaministiquia series. That the Vermilion Lake conglomerate is unconformably above the schists in vertical attitude, bearing ore and jasper, is further indicated by the fact, discovered by Merriam, that on the islands of Vermilion Lake the conglomerate is found to be in a series of gentle folds although having a vertical cleavage developed. Merriam regards the conglomerate as a comparatively thin formation overlying and overlapping the Lower series. Both the Animikie and Upper Vermilion are unquestionably separated from the Lower Vermilion by an unconformity. The Animikie is believed to be the equivalent of the Upper Vermilion.

It is concluded that the confusion in correlation of the formations about Lake Superior is due to the failure to recognize this general unconformity. Once recognized, the structural conclusions to which the various writers have most steadfastly held are found to be in general harmony. Above the physical break, and constituting the Upper Huronian (equivalent to the Original Huronian) are the Animikie and the Upper Kaministiquia, Upper Vermilion, Upper Marquette, Western Menominee, Penokee-Gogebic proper, the Dakota, Iowa, Minnesota, and Wisconsin quartzites surrounded by the fossiliferous series. In the Lower Huronian is the Kewatin (in part at least), the Lower Kaministiquia, Lower Vermilion, Lower Marquette, Felch Mountain iron-bearing series, Menominee proper, and the Cherty limestone at the base of the Penokee series, and the Black River Falls iron-bearing schists.

LAWSON, ANDREW C. Lake Superior stratigraphy: Am. Geologist, Vol. VII, 1891, pp. 320–327.

Lawson discusses Lake Superior stratigraphy in an article which owes its inception to the paper by Prof. C. R. Van Hise entitled "An attempt to harmonize some apparently conflicting views of Lake Superior stratigraphy,"[a] which is abstracted above, p. 97.

Lawson argues for the indivisibility of the Archean, meaning by this term all those rocks that existed prior to the denudation epoch, during which time the floor was formed on which has since been deposited with strong unconformity the Animikie series and its equivalents. The Archean thus includes, in upward succession, the Laurentian gneiss and granite, the crystalline schists of the Coutchiching, and the crystalline schist and clastics of the Keewatin. The Coutchiching and Keewatin are so knit together by the Laurentian foliated granite as to warrant the union of all of these under the term Archean.

Lawson then argues against Van Hise's correlation of the Upper Vermilion with the Animikie series. He states that the granite of Saganaga Lake is found, with abundant and clearly observed evidences of eruption, breaking through the Keewatin rocks, including the Upper Vermilion (Van Hise) fragmental rocks of Ogishki Lake with their associated slates and grits. It is concluded that the break between the Upper and the Lower Vermilion described by Van Hise is within the Keewatin group, dividing it into an upper and a lower series, and that this break is therefore below the Animikie; that these series are united by the Saganaga granite intrusions and that they belong in the schist-granite-gneiss complex of the Archean; hence this break is below the Animikie. It is further said that the conglomerates of the Upper Kaministiquia series come out close to the shores of Thunder Bay and form the basement upon which the undisturbed Animikie rock rests with strongly marked unconformity. The following succession for the region northwest of Lake Superior is presented:

Paleozoic—Algonkian system	Keweenawan, or Nipigon group.
	Unconformity.
	Animikie group (possibly Huronian).

[a] Am. Jour. Sci., 3d series, Vol. XLI, 1891, pp. 117–137.

Unconformity. Greatest erosion interval in American geology.

- Archean
  - Ontarian system
    - Keewatin group (possibly Huronian)
      - Upper series.
      - Van Hise's break.
      - Lower series.
    - Unconformity (?).
    - Coutchiching group.
  - Irruptive unconformity.
  - Laurentian system.

WINCHELL, N. H. Record of field observations in 1888 and 1889: Eighteenth Ann. Rept. Geol. and Nat. Hist. Survey of Minn., for 1889, 1891, pp. 7–47.

N. H. Winchell in 1891 gives numerous additional field observations. The relations of the jaspilite, argillite, and green schist are considered, and the argillite at least is regarded as a sedimentary rock (p. 9). In the Stuntz conglomerate is found a large bowlder which contains pebbles of chalcedonic quartz and quartzose felsite—these contain pebbles of vitreous quartz—and pebbles resembling the porphyrel at Kekekebic [Cacaquabic] Lake (p. 31). A study of the ore formation leads to the conclusion that—

All three of the known agencies for rock forming were intermittently at work and concerned in the formation of the iron ore, viz: Eruption to afford the basic eruptive material; sedimentation, to arrange it (in the main), and chemical precipitation in the same water, to give the pure hematite and chalcedonic silica [p. 42].

The following facts are given as evidence that the Great gabbro of the Cupriferous formation lies below the Animikie slates and that the Keweenawan includes both the Animikie slate and the Huronian (Potsdam) quartzite.

The most important and significant fact that bears on the stratigraphical position of the gabbro, respecting its relation to the Animike black slates, is its occurrence along a wide extent, reaching from Gunflint Lake as far southwestward as to the railroad crossing at Mallmann's (at least), next to and immediately south either of the gneiss of the Giant's range or of the "greenstones" of the Kawishiwin, without the appearance of any of the black slates between them. There is an appearance of quartzite, with olivine grains and with magnitite, geographically between the gneiss and the gabbro, the same being unquestionably the Pewabic quartzite seen near Gunflint Lake. This quartzite is sometimes impure and limonitic, and seems to be the chief iron horizon of the Mesabi range. This near conjunction (which is sometimes apparently an exact contact) of the gabbro with the gneiss, and the absence of the Animikie proper between them, has been supposed to be due to a local overlap of the gabbro beyond the strike of the Animike, covering it from sight, the idea being that the gabbro flowed back northward over older formations and came onto the gneiss [pp. 44–45].

Bowlders of characteristic gabbro and red syenite, and of quartz porphyry, occur abundantly in the later "traps" of the Cupriferous [p. 45].

WINCHELL, H. V. Geological age of the Saganaga syenite: Am. Jour. Sci., 3d series, Vol. XLI, 1891, 386–390.

H. V. Winchell in 1891 states that the syenite of Saganaga Lake is conglomeratic in places and contains pebbles which are similar to each other, being mostly composed of lamellar augite, with or without grains of feldspar, but there are no pebbles of sedimentary rocks or of syenite or jasper such as occur in the Kewatin conglomerates.

In the Saganaga syenite at the end of the portage on Granite River is a band of silica 1½ inches in diameter and 3 feet in length. This is presumed to have been formed by chemical precipitation from heated oceanic waters.[a]

North of Saganaga Lake the syenite grades into greenish feldspathic and sericitic schists and agglomerates without the usual intervening belt of crystalline Vermilion schists. From these facts it is concluded that the syenite is simply the result of the locally intense metamorphism of Kewatin rocks, and is thus of Kewatin age.

Finally, as bearing upon the economic side of the question it is suggested that—

If the Saganaga syenite be of the Keewatin age and contain chalcedonic silica in an original, unchanged condition it is not unlikely to contain also Keewatin iron-ore deposits free from titanium and of high grade in other respects. It can thus no longer be laid down as a law for explorers in the Northwest that the gneisses contain no iron-ore deposits [p. 390].

WINCHELL, N. H. and H. V., The iron ores of Minnesota, Bull. No. 6, Minn. Geol. and Nat. Hist. Survey, 1891, 430 pages, with geological map and section.

N. H. and H. V. Winchell in 1891 give an extended treatment of the iron ores of northeastern Minnesota and the rocks in which they are contained. Magnetic iron ore is not of great importance. Isolated deposits are reported in the mica-hornblende-schists and in a massive hornblende-mica rock of

[a] Winchell, N. H. and H. V., On a possible chemical origin of the iron ores of the Keewatin in Minnesota: Proc. Am. Assoc. Adv. Sci., Thirty-eighth Meeting, 1890, pp. 235–242. Am. Geologist, Vol. IV, 1891, pp. 291–300; 382–386. Also The iron ores of Minn., Geol. Nat. Hist. Survey Minn., 1889, Bull. No. 6, 430 pages.

the Vermilion series. Deposits in the schists are presumed to be of sedimentary origin, the magnetite having been produced by hydrothermal action from hematite, like that of the Keewatin. Those magnetites in the massive rocks are of igneous origin and are analogous to the titaniferous magnetite found in the gabbro.

Hematite is the only ore actually mined on the Vermilion range up to this time, and therefore the deposits of iron of this character are the most important and the ones with which this report chiefly deals.

The ore is always found in schistose or massive greenstone of Keewatin age and is always associated with jaspilite. The ore bodies vary much in size and are of lenticular shape, with long axis trending southwest-northeast, parallel to the schistosity of the inclosing schists.

The jaspilite and schist of the Keewatin are found to occur sometimes minutely interlaminated; at other times the jasper is in irregular layers, which never have any great extent, and finally always pinch out; at other times it is in oval forms, the greater lengths being parallel with the schistose structure. Again, the jaspilite is in great fragments within the green or massive diabasic schists, the masses having sometimes such relations with each other as to show that they are a broken continuous layer. The branches from the large bodies of jaspilite are supposed to be caused by the crumpling, breaking, and squeezing of the entire rock structure, by which the thinner sheets have been buckled out and thrust laterally among the inclosing schists. The ore and jasper are regarded as a direct chemical deep-sea precipitate from an ocean of hot alkalinic water which was continually disturbed by acid rains and flows of basic lava due to volcanic activity. The iron for the ore was extracted from the basic lavas.

The rocks of the Animikie, equivalent to the Huronian and included in the Taconic, consist chiefly of carbonaceous and argillaceous slates, with siliceous slates, fine-grained quartzites, and gray limestones. At the bottom of the series is a fragmental quartz sandstone, 300 feet in thickness, which is named the Pewabic quartzite. The slates, conglomerates, and quartzites are profoundly affected and intermingled with eruptive material similar to that found so abundantly in the Kewatin. These beds have the appearance of consolidated beds of basic lava or of porous tuff, but where this prevails there is a sensible gradation from the dark trap-looking beds to the thin beds of slate. At Ogishke Muncie Lake there is a slate conglomerate similar to that on the north shore of Lake Huron. This conglomerate is not the same as the agglomerates of the Kewatin, such as that on Stuntz Island, at Vermilion Lake, and Ely. The Kewatin is always nearly vertical, while the dip of the Taconic rarely exceeds 15°. The iron-ore beds of the Taconic are: (1) The quartzose, hornblendic (or olivinitic), magnetitic group of the Pewabic quartzite; (2) an impure jaspilite, hematite, and limonite group; (3) a carbonated iron group; (4) a gabbro titanic iron group. The jaspilitic hematite group has the same lithologic peculiarities as the jaspilite beds of the Vermilion range. The gabbro in which the titanic iron occurs constitutes the Mesabi range. This has been before regarded as the base of the Keweenawan, into which it fades upwardly, but it has been found that this great gabbro flow was outpoured at an earlier date, and it is placed at or near the bottom of the Animikie.

Considered as to origin, the ores of the Taconic found in groups 1 and 2 above are supposed to be due to chemical oceanic precipitation. Those of group 4 are of igneous origin and are an integral part of the gabbro The origin of those of group 3 is not definitely stated (pp. 144–145). None of these Taconic ores are thus far mined in Minnesota.

1892.

Bayley, W. S. Notes on the petrography and geology of the Akeley Lake region in northeastern Minnesota: Nineteenth Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1890, 1892, pp. 193–210.

This is chiefly a petrographic description of rocks from Akeley Lake. The three important results reached, largely by the microscopic study, are summarized as follows:

(1) Most of the rocks designated as Pewabic quartzite in the neighborhood of Akeley Lake are not quartzites, but they are granulitic phases of gabbro. The remainder are crystallized aggregates of quartz. None of them are sedimentary rocks, and consequently none can serve to determine the age of the ore associated with them or of the gabbro in which they occur.

(2) On the other hand, the granulitic gabbros may be traced into true granitic gabbros and into quartzose phases of granulitic varieties. Hence, the granulitic beds and their associated ores are of the same age as the gabbro, whose structural relations to the younger and older formations must be appealed to in order to settle the question of age.

(3) Since so much of the "Pewabic quartzite" is not quartzite in any sense of the word, and since different beds that have been given this name are not all certainly

of the same age, it is evident that great care must be taken in the use of the "Pewabic quartzite" for correlation purposes. Several different rocks have been included under this one title, hence the "Pewabic quartzite" as defined can not be relied upon as marking a definite horizon in the succession of the geological formations in northeastern Minnesota [pp. 208–209].

In an appendix Dr. Bayley states that the first two of the above conclusions had been reached by W. M. Chauvenet a number of years before, as the result of work done in the vicinity of Akeley Lake for the Lake Superior division of the United States Geological Survey in 1883 and 1884. Dr. Bayley was not aware of Mr. Chauvenet's conclusions until after his own had been arrived at, Mr Chauvenet's being contained in an unpublished report submitted to Prof. R. D. Irving (p. 209).

WINCHELL, N. H. The Kawishiwin agglomerate at Ely, Minn.: Am. Geologist, Vol. IX, 1892, pp. 359–368.

This article contains a description of a greenstone which is found in the Keewatin of the Vermilion district of Minnesota and which possesses a peculiar structure.

On clean exposures the greenstone is seen to be not homogeneously massive, but to be composed of irregularly rounded to oval bodies of massive greenstone ranging from 6 to 15 inches in diameter, surrounded by and separated from each other by relatively narrow masses of fine-grained chloritic schist, which winds about among the masses, its schistosity coinciding with the surfaces with which it is in contact. The peripheries of these massive bodies are all amygdaloidal, the long direction of the pores being perpendicular to the surface of the round body.

The author explains the rock as an agglomerate, the rounded bodies being bombs that were hurled into the air by volcanic forces and fell into a hot ocean, in which was being deposited a fine volcanic mud which now forms the fine schist between the bombs. In other words, "The source of such rocks was igneous, but their structure is aqueous" (p. 367).

VAN HISE, C. R. Correlation papers, Archean and Algonkian: Bull. U. S. Geol. Survey No. 86, 1892, pp. 51–208, map, Pl. III, op. p. 52, and pp. 440–529.

This bulletin, on the pages indicated, contains a thorough digest of the various articles that had appeared concerning the Lake Superior pre-Cambrian geology prior to the time of its publication. The author's interpretation of the structure and stratigraphy of the various regions is based upon his very wide personal knowledge of the occurrences described in the articles, and this lends additional value to his opinion.

The following are his conclusions about the Vermilion district, with which we are especially interested. The succession, compared with that of the Marquette district of the south shore of Lake Superior, which, having been carefully worked out, we can use as a standard, is as follows (p. 195):

	Northern Minnesota.	Marquette (Michigan) district.
Algonkian	Keweenawan.	
	Unconformity.	
	Animikie and Upper Vermilion.	Upper Marquette.
	Unconformity.	Unconformity.
	Lower Vermilion.	Lower Marquette.
	Unconformity (?).	Unconformity.
Archean	(Coutchiching?).	
	Eruptive unconformity.	Fundamental complex (not yet separated in mapping).
	Laurentian.	

GRANT, U. S. The stratigraphic position of the Ogishke conglomerate of northeastern Minnesota: Am. Geologist, Vol. X, 1892, pp. 4–10.

Grant states that the Animikie rests unconformably upon the Saganaga granite; that the Ogishke conglomerate is intruded by the Saganaga granite, and therefore that the Ogishke conglomerate is earlier than and separated by a great structural break from the Saganaga granite. As the Keewatin has the same relations to the Saganaga granite as the Ogishke conglomerate, the same thing is true of the Animikie and Keewatin.

The Ogishke conglomerate is younger than the most of Keewatin, but is considered as a part of it.

1893.

VAN HISE, C. R. An historical sketch of the Lake Superior region to Cambrian time: Jour. Geol., Vol. I, 1893, pp. 113–128.

In this historical sketch the five subdivisions given for this region are the Basement complex or Archean, the Lower Huronian, Upper Huronian, and Keweenawan, the last three together constituting the Algonkian and the Lake Superior (Cambrian) sandstone. Each of these divisions is separated from the others by unconformities. The only rocks of the Vermilion district treated of are the Lower Vermilion and the Animikie series, the Lower Vermilion series being placed in the Lower Huronian and the Animikie being placed in the Upper Huronian.

The Lower Huronian is largely crystalline; the Upper Huronian semicrystalline. Locally, along axes of intense plication, both the Lower Huronian and Upper Huronian have been transformed into completely crystalline schists.

Winchell, N. H. The crystalline rocks—some preliminary considerations as to their structure and origin: Twentieth Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1891. 1893. pp. 1–28.

In this article Professor Winchell gives the following as the descending succession of strata in northeastern Minnesota. This determination of the succession represents, according to him, the consensus of opinion of several geologists who have given special attention to the field evidences. From this statement must, however, be excepted the Great gabbro horizon, No. 3, as by some it is presumed to have preceded, and not to have followed, the Pewabic quartzite.

1. Keweenawan or Nipigon series, unconformably beneath rocks bearing the "Dikellocephalus" fauna, and consisting of fragmental and eruptive beds, the upper portions being almost entirely red sandstones.

2. Alternating beds of eruptive sheets and fragmental rocks. The fragmentals are thin-bedded slates, actinolite-schists, magnetitic jaspers, cherts, and quartzites. The sheets are ordinary eruptives or pyroclastics.

3 Immense quantities of true gabbro, often bearing titaniferous magnetite, are associated with contemporaneous felsites, quartz-porphyries, and red granites. This gabbro includes several masses of the next older strata, particularly the Pewabic quartzite.

4. The Animikie. This series is characterized by a great quartzite associated with the iron ores and cherts. The quartzite (Pewabic) lies unconformably on all the older rocks. It is often conglomeratic, bearing débris of the underlying formations. Within it is mingled volcanic tuffs from contemporaneous eruptions. The Pewabic quartzite includes that of Pokegama Falls, on the Mississippi, and of Pipestone County. In the vicinity of contemporaneous volcanic disturbances its grain is fine, like jasper, and sometimes it has acquired a dense crystalline structure from contact with the gabbro.

5. The Keewatin. This is a volcanic series of great thickness, composed mainly of volcanic tuffs, presenting evidence of aqueous sedimen-

tation, but conglomerates, graywackes, quartzitic schists, and glossy serpentinous schists are present. The Kawishiwin formation, apparently the upper member of the series, embraces the great bulk of the greenstones, chloritic schists, jaspers, and hematites. The iron ores are in lenticular lodes, and stand upright, conformable with the general position of the rocks.

6. The Keewatin series becomes more crystalline toward the bottom, and passes conformably into completely crystalline mica-schists and hornblende-schists, which are named the Vermilion series. The rocks are usually stratiform, contain magnetic iron ore, and embrace some dark massive greenstone belts, in which no stratification bands are visible.

7. The Laurentian. When not disturbed by upheaval the Vermilion schists pass into Laurentian gneiss, there being a gradual increase in the feldspathic and siliceous ingredients. Even after the Laurentian characters are apparently fully established, conformable bands of Vermilion schists reappear, from which it is plain that the base of the Vermilion is an uncertain plane, which can not be located exactly. This normal passage from the Vermilion to the Laurentian is frequently disturbed by the intrusion of numerous dikes of light-colored granitic and basic rocks. These were both in a fluid state, the only nonfluid rocks being the schists which are embraced within them in isolated pieces. In a similar manner small areas of Laurentian granite are sometimes directly in contact with schists, which have the imperfectly crystalline condition of the Keewatin.

Nos. 3 and 4 are separable from No. 2 by divergence in dip and strike, as well as by a marked difference of lithology. There is consequently some evidence of unconformity between them. Below No. 4 is a great physical break, which separates Nos. 1, 2, 3, and 4 from 5, 6, and 7 throughout the Lake Superior region. This break is the greatest erosion interval which has been discovered in Paleozoic geology. Nos. 1, 2, 3, and 4 together constitute the Taconic. Nos. 5, 6, and 7 constitute the fundamental complex or Archean, which is a unit in its grander features.

Grant, U. S. Field observations on certain granitic areas in northeastern Minnesota: Twentieth Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1891, 1893, pp. 35–110. One map.

Grant, in 1893, publishes his notes made on a trip in northeastern Minnesota. The areas visited were those of Kawishiwi River, Snowbank Lake, Kekequabic [Cacaquabic] Lake, and Saganaga Lake.

In the study of these areas there was no evidence found of a transition from semicrystalline and crystalline schists into granite. On the other hand, abundant evidence was found of the irruptive nature of the granite rocks into the surrounding sediments. The Kawishiwi River and Snowbank Lake massive rocks are hornblende-syenites. The Saganaga rock is a coarse hornblene-granite. That around Kekequabic Lake is a pyroxene granite, and associated with it is peculiar pyroxene-granite-porphyry (pp. 37–38).

The intrusive character of the granite is particularly well shown where the line between secs. 31 and 32, T. 63 N., R. 10 W., cuts the shore of Clearwater Lake, and in the SE. ¼ of the SW. ¼ sec. 26, T. 64 N., R. 9 W., on the west shore of Snowbank Lake.

> [Along] the Kawishiwi River . . . five distinct rock types [gabbro, syenite, mica-schist, graywacke, etc., greenstone, and quartz-porphyry] are present. The gabbro is the most recent; it covers part of the older rocks. . . . The syenite is older than the gabbro and is younger than the greenstone and mica-schist, both of which it cuts. . . . The mica-schists, graywackes, etc., stand vertical, and have a general east-northeast strike; they belong to what has been mapped as the Vermilion series, but there seems to be good reason for putting all of this type of rocks, in the area of this map, into the Keewatin. The greenstone is presumably of Keewatin age, and is probably younger than the mica-schists, graywackes, etc. Quartz-porphyry dikes are found cutting the greenstones in several places, but they have not been seen in the other rocks in this immediate vicinity [p. 59].

The conclusions of this report differ from the general succession given by Professor Winchell in the fundamental point that there is no gradation between the granitic rocks and the metamorphosed sedimentary rocks. Also all of the metamorphosed sedimentary rocks are regarded as belonging to the Keewatin (Lower Huronian ?), while the Vermilion schists are not found. If there now exists in this area the original basement upon which the sedimentary rocks were deposited, this has not been found. It is of course possible that such a Basement complex does not exist in the Kawishiwi River area, the one which was most closely studied.

GRANT, U. S. The geology of Kekequabic Lake in northeastern Minnesota, with special reference to an augite soda-granite: Twenty-first Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1892, 1893, pp. 5–58. With map, Pl. II.

In this article Grant describes in great detail an area approximately 5 miles square surrounding Kekequabic Lake. The distribution of the various kinds of rocks present in the area is carefully determined and represented upon the map (Pl. II), which accompanies the article. With the exception of the Keweenawan gabbro and certain diabase dikes, whose age is undetermined, all the rocks described are included in the Keewatin. The points of chief interest in the paper are of a petrographic character, and consist in a description of some anomalous green schists, of a hornblende-porphyrite, and of an augite soda-granite. Evidence is also presented to show that this is a true igneous granite, and is not due to crystallization of sediments in situ, as had been previously maintained in papers on the region by other writers.

1894.

Grant, U. S. Preliminary report of field work during 1893 in northeastern Minnesota: Twenty-second Ann. Rept. Geol. and Nat. Hist. Survey Minn., for 1893, 1894, pp. 67–78.

That part of the region studied by Mr. Grant, which is included in the Vermilion district as described in this paper, lies in the Gunflint Lake area, north of T. 63 N., and between Rs. 3 and 7 W. In Ts. 65 and 66 N., Rs. 4, 5, and 6 W., are Keewatin rocks, including the usual types—volcanic tuff, greenstone-schists, greenstone, and the Ogishke conglomerate. The Saganaga granite is intrusive in the Keewatin, the rocks of which it metamorphoses. The author feels himself justified in stating:

> (1) That the rocks called Vermilion in the region of the writer's field work are not necessarily lower in the geological scale than the Keewatin, but that they occur at various horizons in the Keewatin; (2) that they are only a more crystalline condition of these same Keewatin rocks; and (3) that they probably owe their more crystalline nature largely to their close proximity to areas of intrusive granite [p. 71].

The Animikie iron-bearing rocks of Akeley Lake lie upon the Keewatin greenstone to the north, and on the south are overlain by the Great gabbro mass. The belt has a width of from 300 to 1,300 feet and a dip varying from 20° to almost vertical, but averaging 45° to 50°. Where widest it has an average dip of 30°, which would make a maximum thickness of 650 feet. The iron ore is a nontitaniferous magnetite.

The Animikie rocks are little disturbed, except locally, having an average dip of 8° or 10° a little east of south. The Animikie beds are interleaved with diabase sills. These give parallel east-west ridges, which are gently sloping on the south sides, and steep on the north. This topography has led Lawson to the conclusion that the apparent large number of sills is due to monoclinal faulting of fewer layers, but of this there is no evidence. The Animikie strata are divided as follows: An upper or graywacke-slate member, 1,900 feet thick, composed of slates and graywackes, with fine-grained quartzites and quartz-slates; a middle or black slate member, 1,050 feet thick, composed mainly of black slates, apparently carbonaceous, with a fine-grained, siliceous and flinty layer at the base 60 feet thick; and a lower or iron-bearing member, composed largely of jaspery, actinolitic, siliceous, and magnetitic slates, usually thinly laminated, and some beds of cherty iron carbonate.

The Akeley Lake rocks, first called Pewabic quartzite, are similar to the Gunflint iron-bearing rocks, and different from the Pewabic quartzite and conglomerate found at the base of the Animikie farther west on the Mesabi range. From the new data obtained, the Akeley Lake iron-bearing rocks, which rest directly upon the Keewatin, are placed as the iron-bearing member above the Pewabic quartzite.

Elftman, A. H. Preliminary report of field work during 1893 in northeastern Minnesota: Twenty-second Ann. Rept. Geol. and Nat. Hist. Survey of Minn., for 1893, 1894, pp. 141–180.

This contains many details concerning the structure and character of the rocks north and west of Snowbank Lake. A section is given from Moose Lake to Snowbank Lake, showing relations of rocks in the intervening area as determined by him.

Interest centers in the porphyry and granite. The porphyry is the oldest eruptive. It is found sending long apophyses across the strike of the Keewatin rocks, and contorting and metamorphosing them. On Snowbank Lake there are two granites, a red hornblende- and a gray augite-granite, formerly known as red syenite and gray syenite, respectively, which are considered as having been derived from parts of the same magma. The gray augite-granite is not found in contact with the sediments. This augite-granite, the porphyry referred to above, and also the sediments are cut by the hornblende-granite. Where the sediments are cut by the granite they are metamorphosed to schists.

In connection with the preceding it might be of interest to note that the hornblende and mica schists of Snowbank and White Iron lakes grade into argillaceous slates and conglomerates. The schistose character is most fully developed at the contact with the granite. All evidence tends to show that the schists are due to the intrusion of the granite, and suggests that the narrow belts of schist generally found between the granite and the Keewatin rocks, and which have hitherto been designated as a separate formation (Coutchiching or Vermilion) are only altered portions of the Keewatin, which have been subjected to the heat and action of the intrusive granite [p. 159].

The author also adduces further evidence to prove that, in accord with Dr. Grant's statement to the same effect, the so-called Pewabic quartzite between Birch and Gunflint lakes belongs in reality to the middle iron-bearing member of the Animikie. (Cf. abstract of Grant's report above.)

1895.

Smyth, H. L., and Finlay, J. Ralph. The geological structure of the western part of the Vermilion range, Minnesota: Trans. Am. Inst. Min. Engineers, Vol. XXV, 1895, pp. 595–645.

Smyth and Finlay describe the western part of the Vermilion range. The sedimentary rocks fall into two divisions. The older is a fragmental slate formation, while the younger is an iron-bearing formation lithologically identical with certain phases of the lower iron-bearing formation of the Marquette district. To all appearances it is devoid of clastic material. It is believed, from analogies with other iron-bearing districts of the Lake Superior region, that the jasper of the Vermilion district is derived from a cherty iron carbonate or from a glauconite greensand, or both. However, as the jasper is a final product of the alterations, it is not possible to show this.

Intrusive igneous rocks are very abundant, cutting or being interleaved with the sedimentary rocks in masses running from the thickness of a knife blade to those 100 feet across. In quantity the igneous rocks exceed, perhaps, several times the sedimentary rocks. The oldest igneous rocks are greenstones. These vary from massive to schistose, and in some places are what is called conglomerate breccias. The acid rocks were intruded later than the basic rocks. They were originally for the most part quartz-porphyries, but these have been extensively changed to sericite-schists and conglomerate breccias and to rocks intermediate between these and the original form. Within the larger masses of the igneous rocks, both basic and acid, are frequently included fragments from both the slate and iron formations, from those of small size to masses more than 100 feet long.

The conglomerate breccias are of dynamic origin. The first step in the development of the breccias was the formation of two intersecting sets of planes of fracture, dividing the originally massive rocks into roughly rhomboidal blocks. Their further development depended on continued movement between these blocks under pressure, which resulted in enlarging the shearing zones at the surfaces of contact, and rounding the angles. The slate and jasper inclusions originally plucked off from the rocks which the porphyries and greenstones invaded shared, of course, the subsequent history of their captors. The fact that the jasper inclusions are frequently rounded, while those of slate are not, is explained by the difference in the elasticity of the two rocks. The slate inclusions readily yielded and finally took a permanent set under the deforming forces, while the harder and more rigid jasper, in fragments of limited size and diverse orientation, behaved like the inclosing porphyry. The boundaries of the inclusions were generally the surfaces along which rupture took place, although, as has already been said, jasper in a few instances is found partly held in porphyry inclusions.

As to structure, the main slate area is anticlinal; both north and south of this area the jasper succeeds the slates. The southern jasper continues in a complex syncline, and south of this is found the northern limb of another anticline of slates, the southern limb not being exposed. Still farther south is the jasper of Lee and Tower hills, which appears to form the southern and western edges of a complex syncline. All of these folds pitch toward the east.

The ore deposits, a number of figures of which are given, as well as many details concerning them, are found to conform in occurrence to the laws worked out by Van Hise in reference to other districts of the Lake Superior region; that is, (1) they occur for the most part in pitching troughs having impervious basements, the basement being usually one or more of the different varieties of the eruptive rocks; (2) they are secondary concentrations produced by downward-percolating waters, the silica being leached out and the iron deposited.

1896.

Elftman, Arthur H. Ore deposits of Minnesota: Engineers' Year Book, Univ. of Minn., 1896, pp. 115–117.

This is a brief statement of the ores known to exist in the State. Of a number mentioned, the iron-ore deposits are the only ones which have been developed to any extent. These deposits occur in the Vermilion and Mesabi ranges. In the Vermilion the ore is a hematite, with low content of phosphorus and sulphur, ranging from soft to hard ore. The deposits are in the Keewatin of the Lower Huronian, and are mined only at Tower and Ely. Eastward from Ely, extending through the eastern part of Hunters Island, are very favorable indications of ore deposits.

1897.

Eby, J. H., and Berkey, Chas. P. Copper minerals in hematite ore: Engineers' Year Book, Univ. of Minn., 1897, pp. 108–117. (Reprinted from Proc. Lake Superior Min. Inst.)

Mr. Eby describes the occurrence of a number of copper minerals in the hematite ore of the Montana mine, of Soudan, Minn. The minerals associated with the native copper found in the hematite are cuprite, malachite, azurite, and chalcopyrite. The native copper seems to have been the source of the copper minerals, as in one case an octahedron was found which consisted of metallic copper at center, surrounded by layers of cuprite (CuO), and this surrounded by copper carbonate.

Mr. Berkey describes the minerals, excepting the chalcopyrite, which was not found in the specimens he had for study.

Winchell, N. H. Some new features in the geology of northeastern Minnesota: Am. Geologist, Vol. XX, 1897, pp. 41–51.

Winchell presents some additional points on the geology of northeastern Minnesota.

The Laurentian includes, in Minnesota, an acid crystalline schist of sedimentary origin and a massive igneous rock, although the igneous rock is younger than the crystalline schist portion and should have a different designation. The conclusions reached are that (1) the sedimentary Laurentian is a crystalline condition of sedimentary strata, which are conformably a portion of the sedimentary schists; (2) the igneous Laurentian is the result of a more intense metamorphism, carried even to fusion of some strata. These conclusions result particularly from the study of a section from Tower northward through Vermilion Lake, and of an area on the west side of Outlet Bay, in the corners of secs. 13, 14, 21, and 32, T. 63 N., R. 17 W., and along the shore for one-half mile westward.

It is evident that the Stuntz conglomerate on the south shore of Vermilion Lake is a true water-deposited conglomerate of the same formation as the slates and graywackes of the district, the conglomerate grading into the quartzite and graywacke, and this into argillaceous slate. Furthermore, as supposed by Van Hise, the conglomerate lies unconformably on the iron-bearing formation, and contains very numerous fragments of jaspilite. The position of this unconformity, whether at the base of the Taconic or lower, is not ascertained.

1898.

Grant, U. S. Sketch of the geology of the eastern end of the Mesabi iron range in Minnesota: Engineers' Year Book. Univ. of Minn., 1898, pp. 49–62; with sketch map.

Grant sketches the geology of the eastern end of the Mesabi iron range in Minnesota, including T. 64 N., Rs. 3 and 4 W., and parts of Rs. 2 and 5 W., with some adjacent portions of Ontario. The rocks can be separated into three divisions. The chief one of these is the Animikie series, containing the iron-bearing rocks of the Mesabi range. Older than the Animikie is a series of granites, greenstone both massive and schistose, conglomerates, slates, and other clastic rocks, called the pre-Animikie. Younger than the Animikie are some diabase sills and the Great gabbro mass of northeastern Minnesota.

Of the pre-Animikie rocks, the greenstones and clastic rocks have been called Keewatin. As the greenstones are usually associated with the Mesabi iron-bearing rocks, these alone of the Keewatin rocks are described. They lie to the north of the iron-bearing rocks in T. 65 N., R. 5 W., and extend eastward to the center of T. 65 N., R. 4 W., where they disappear under the Animikie strata. In general, the greenstones are at present diorites; originally some were certainly diabases, others were of the nature of andesites, and a large part were diorites or possibly gabbros. At places, especially along the east side of sec. 27, T. 65 N., R. 5 W., the greenstones contain angular and subangular fragments of rock almost like themselves, and some may be regarded as composed of fragmental volcanic rocks. Associated with the greenstones, especially in secs. 22, 23, and 24, T. 65 N., R. 5 W., are small masses of more acid rocks, quartz-porphyries, and quartzless porphyries, which are probably younger than the greenstones.

The pre-Animikie granite has its typical development on the shores of Saganaga Lake. In a number of places it may be seen in intrusive relations with the greenstone. A quarter of a mile south of the northeast corner of sec. 23, T. 65 N., R. 5 W., many granite dikes cutting the greenstone are seen, and on the south shore of West Sea Gull Lake granite dikes of the same nature as the immediately adjacent main mass of granite of Saganaga Lake are seen cutting the greenstone. Both granite and greenstone are cut by another series of finer-grained, more acid granite dikes.

The Animikie rocks rest uncomformably upon the pre-Animikie rocks, and are usually exposed on the south slope of the Giants range, which is composed essentially of granite. The strike is approximately east-northeast, and the dip in general about 10° SE. The thickness varies from nothing to 4,000 feet. The Animikie is separable into four conformable divisions—(1) the lower or quartzite member, called the Pewabic quartzite; (2) the iron-bearing or taconite member; (3) the black-slate member; (4) the graywacke-slate member.

(1) The quartzite member is well developed in Itasca County, but disappears before reaching the eastern side of St. Louis County.

(2) The rocks of the iron-bearing member are similar to those in St. Louis County on the western end of the range, described by Spurr.[a] They differ, however, in two features. They are more completely crystalline, and the iron is magnetite instead of hematite. The rocks consist chiefly of jaspers, amphibole- (grünerite) schists, greenish siliceous slates, cherts, cherty carbonates, and magnetite slates. It is believed that these rocks were originally glauconitic greensands; that the ore has been derived from the iron in the glauconite, and that the ore bodies result from concentration and replacement. In this part of the Mesabi range no ore bodies have yet been found which are at the same time both rich enough and large enough for profitable mining, although vast quantities of magnetite ore

[a]Geol. and Nat. Hist. Survey Minnesota, Bull. No. 10, 1894.

occur at or near the surface. The dip of this formation varies from an average of 45° to 50° on the west to less than 15° on the east, and the thickness varies from 650 feet or less on the west to 900 feet on the east.

(3) The black slate is essentially a fine-grained, black, more or less siliceous, apparently carbonaceous slate.

(4) The graywacke-slate member is composed of black to gray slates and fine graywackes, with some flinty slates; the upper part shows coarser detrital material, and the highest beds seen are fine-grained quartzites and quartz-slates. This member is well exposed on the south shore of Loon Lake.

Associated with all of the strata of the Animikie are diabase sills, and bounding the Animikie rocks on the south is the Great gabbro mass. These are igneous rocks of later date than the Animikie. Near the contact with the gabbro the Animikie rocks show marked metamorphism and usually complete recrystallization. The gabbro varies from a nearly pure plagioclase rock to titaniferous magnetite.

The pre-Animikie rocks here described, according to the nomenclature used by the United States Geological Survey, belong to the Lower Huronian series of the Algonkian system, and probably also in part to the older Archean or Basement complex; the Animikie is regarded as the equivalent of the Upper Huronian series of the Algonkian, and the gabbro as a part of the Keweenawan series of the Algonkian.

1899.

Sardeson, F. W. Report of secretary of the Geological Club of the University of Minnesota: Science, Vol. IX, pp. 412–413.

Prof. C. W. Hall discusses "The extent and distribution of the Archean in Minnesota." The following quotations are from the secretary's report:

> Accepting the Archean as that original "crust" or solidified portion of the earth, . . . he defined it as an era of igneous origins, whose rocks represent the original crystallization of earth matter added to from below by successive solidification and many subsequent intrusions. By this definition all overlying clastics or irruptions into or through the clastics are excluded from the Archean. . . .
>
> Between Rainy Lake and Lake Superior there are several belts of schists, with alternating granites and other rocks having a general northeast-and-southwest trend. Concerning one of these, Irving noted in 1886 "that we have among the rocks . . . two types, in one of which the crystalline structure is complete and in which there is

little or none of an original fragmental structure, while in the other the fragmental texture is still distinct and the alteration has progressed to a smaller degree." He then adds "that the supposed older one of the two groups of schists in the Vermilion Lake belt is intricately penetrated by the granites of the great areas north and south of the belt."[a] Hence areas of Archean lie north and south of these older schists.

It is clear that Professor Hall believes in the presence of Archean rocks in the Vermilion district, although the careful reader will see that Professor Hall's conclusion as to their occurrence there does not follow from his definition of Archean as reported here and from the quotation from Professor Irving's report.

WINCHELL, N. H., GRANT, U. S., and ELFTMAN, A. H. Twenty-fourth Annual Report Geol. and Nat. Hist. Survey of Minnesota for years 1895–1898, 1899.

In this annual report, which it is stated is the final one, there are published the lists of rock specimens, with annotations, collected by N. H. Winchell in 1896, 1897, 1898; a record of the field work of U. S. Grant, 1892–1898, and a list of specimens collected by him in 1898; also a list of specimens collected by A. H. Elftman in 1895, 1896, 1897.

In these we find statements concerning the Vermilion district, but the material is not digested, and no general conclusions are stated. Consequently it is impracticable to review the report and show its actual contents.

WINCHELL, N. H., et al. The geology of Minnesota, by N. H. Winchell, U. S. Grant, James E. Todd, Warren Upham, and H. V. Winchell: Final Report Geol. and Nat. Hist. Survey of Minn., Vol IV, 1899, pp. 630. With 31 geologic plates.

Structural geology of Minnesota, by N. H. Winchell: Final Report Geol. and Nat. Hist. Survey of Minn., Vol. V, 1900, pp. 1–80, 972–1000.

The first of these volumes contains an account of detailed field work in northeastern Minnesota, with incidental discussion of general problems. The area is treated by counties and smaller arbitrary geographic divisions, in the description of which several men have taken part. This manner of treatment leads to repetition in the discussion of the general geologic features, and in many cases it is extremely difficult to correlate the facts recorded in the different sections.

Volume V contains an account of the general structural geology of the State, by Professor Winchell, based on the detailed work described in

[a] Seventh Ann. Rept. U. S. Geol. Survey, p. 437.

Vol. IV. This general discussion of Vol. V is reviewed, with such reference to the facts recorded in Vol. IV as is necessary to make the summary intelligible.

Dr. Grant's views, as indicated in the detailed descriptions of special areas, in some cases differ somewhat widely from those of Professor Winchell.

Winchell discusses the general structural geology of northeastern Minnesota. The ancient rocks of this area he places in two main systems, the Archean and the Taconic. The former is further subdivided into the Upper and Lower Keewatin, separated from each other by an unconformity. The Pewabic quartzite also is placed with the Keewatin, but is not assigned to either of the main divisions. Overlying the Archean with strong unconformity is the Taconic, represented by Animikie and Keweenawan rocks, these divisions being supposed to represent, respectively, the Lower and Middle Cambrian of other parts of the country. The Coutchiching and Laurentian rocks before mapped as separate formations are now included within the Keewatin.

The Lower Keewatin comprises greenstone, with associated surface volcanics which are both subaerial and subaqueous, argillitic slates, siliceous schists, quartzites, arkoses, "greenwackes," iron ores, and marble.

The greenstone, designated the Kawishiwin, is the oldest known rock in the State, and is supposed to represent a portion of the original crust of the earth. With its associated volcanic rocks it occurs in two main belts. The southern belt begins in the vicinity of Gunflint Lake and extends indefinitely westward by way of Gobbemichigamma Lake, the Kawishiwi River, White Iron Lake, and Tower. The northern belt of greenstone enters the State from Hunters Island, appearing conspicuously at the south side of Basswood Lake. At Pipestone Rapids and Fall Lake it widens southward and apparently unites at the surface with the southern belt, the overlying Upper Keewatin being absent for a distance of a few miles. But farther west it is again divided by the Stuntz conglomerate, the northern arm running to the north of Vermilion Lake, west of which its extension is unknown, and the southern one running south of the lake.

The fragmental stratified rocks of the Lower Keewatin are most important toward the western part of the area of exposure of crystalline rocks. They occupy a wide area south, west, and north of Tower. The iron ores of Tower and Ely on the Vermilion iron range occur in the upper part of the Lower Keewatin. It is probable that the immediately inclosing rock is a sedimentary one, although composed of the elements of a basic eruptive. The sediments extend south to the Giants range of granite, where they are metamorphosed to mica-schists by the granite. Toward the west they extend as far as the Mississippi River and its northern tributaries and across the Bowstring, although the drift prevents the delimitation of the belt. To the northwest they extend toward Rainy Lake, in this direction being converted into mica-schists and gneisses by the intrusion of granite; in unmodified form they are found at one point only on Rainy Lake. These fragmental rocks of the Lower Keewatin doubtless also underlie most of the central and southwestern part of the State as far as the Minnesota River. Here they dip beneath the later formations in the southwestern portion of the State, and probably occupy a wide patch in South Dakota. South of the Giants range they occur also, but as they are covered by the gabbro and Animikie toward the east and the drift deposits of the St. Louis Valley toward the west their geographic boundaries are mostly unknown. They appear in the central and western portions of Carlton County, where their line of separation from the Upper Keewatin is quite obscure, and in the central and western portions of Morrison County. The Lower Keewatin marble is seen at Ogishke Muncie Lake and at Pike Rapids on the Mississippi.

The Lower Keewatin was terminated by a period of extensive folding and intrusions of granite and basic rocks.

The Pewabic quartzite belongs with the Keewatin, but whether to the Lower or Upper Keewatin is not known. This formation includes altered quartzites and iron ores between the granite and gabbro in the immediate vicinity of Birch Lake and small patches of similar rocks in sec. 30, T. 62 N., R. 10 W.; on the south shore of Disappointment Lake; on the north shore of Fraser Lake; on the south shore of Gobbemichigamma; at Akeley Lake, forming the so-called Akeley Lake series extending from the west side of sec. 34, T. 65 N., R. 5 W., to the eastern part of sec. 27, T. 65 N., R. 4 W.

The Upper Keewatin occurs in troughs in the Lower Keewatin, and particularly in one main trough the axis of which is traceable from Vermilion Lake to Saganaga Lake. The northern arm of this syncline, consisting of granites, gneisses, associated mica-schists, and in some places earlier greenstones, extends from the northern part of Vermilion Lake through Basswood Lake to the northern side of Hunters Island. The southern arm, consisting of Lower Keewatin green schists and other schists, penetrated by the granite of the Giants range, extends from Pokegama Falls on the southwest toward the northeast, until cut out by the encroachment of the gabbro from the south. The Upper Keewatin consists very largely of conglomerates, but also includes graywackes, argillites, quartzites, and jaspilites, in general coarser than those of the Lower Keewatin. Volcanic rocks are less important than in the Lower Keewatin, although still present. There is no general order of succession in the Upper Keewatin excepting that it can be said that it is in general conglomeratic at the bottom.

After Upper Keewatin time both the Lower and Upper Keewatin were subjected to another folding, the axis of which had a general parallelism with the earlier folding, with the result that the Upper Keewatin lies in narrow synclines in the Lower Keewatin and in places is nearly or quite vertical.

Associated with the Keewatin rocks are granites of at least two periods of intrusion, one later than the Lower Keewatin and one later than the Upper Keewatin. The later granite is believed to be represented by the higher parts of the Giants range and the Snowbank Lake granite. The earlier granite is represented by the granites at Kekequabic (Cacaquabic) Lake, Saganaga Lake, Basswood Lake, Burntside Lake, Vermilion Lake, Lac la Croix, and Kabetogama Lake. The origin of the granite is discussed and the same conclusions reached as in a previous article.[a]

The Taconic.—This is unconformably above the Keewatin rocks. It comprises the Animikie and Keweenawan divisions.

The Animikie rocks enter the State at Pigeon Point, run westward along the international boundary to the eastern part of secs. 22 and 27, T. 65 N., R. 4 W. They reappear again southwestward from Birch Lake on the northwest side of the gabbro mass, and thence continue along the south side of the Giants range, constituting the Mesabi iron series, to Pokegama Falls. The higher parts of the Animikie are best developed toward the east while the lower parts are best developed toward the west.

[a] The origin of the Archean igneous rocks, by N. H. Winchell: Proc. Am. Assoc. Adv. Sci., Vol. XLVII, 1898, pp. 303, 304 (Abstract). Also Am. Geologist, Vol. XXII, 1898, pp. 299–310. Summarized Jour. Geol., Vol. VII, 1899, p. 194.

The Animikie rocks comprise the Pokegama quartzite, Mesabi iron-bearing formation, some limestone and slate, all strictly conformable with one another. The thickness is several hundred feet, sometimes reaching nearly 1,000 feet. The dip of the series is uniformly to the south, 8° to 12°.

The iron-bearing formation and the Pokegama quartzite constitute the base of the formation. The quartzite in places is beneath the iron formation; in other places it is in the some horizon, and in still others is above the iron formation. Commonly the base of the Animikie is marked by a conglomerate, containing débris from the underlying Keewatin rocks. This is a narrow horizon which soon graduates upward into a quartzite, known as the Pokegama quartzite, from its typical development near Pokegama Falls on the Mississippi River. The thickness of the quartzite is not known to exceed 50 feet, and is sometimes less than 25 feet.

Above the quartzite, or in alternating beds with it, or below it, appears the iron-bearing or taconite member of the Animikie, which contains the iron-ore deposits of the Mesabi iron range. The ore is usually hematite in the western part of the range and magnetite in the eastern part. It was previously supposed to have been derived from the alteration of a greenish glauconitic sand rock; but later work has seemed to show that the greensand is a volcanic sand, and that the so-called taconitic rock itself has resulted from igneous forces. This is accounted for by supposing a chain of active volcanoes to have existed where the Mesabi iron range is now found. These volcanoes yielded flows and ejectamenta to the adjacent waters which have been modified into the various phases of the iron formation now seen. This volcanic epoch may have a deep-seated connection with the Cabotian or lower division of the Keweenawan (described later).

Above the iron-bearing member is an impure dark colored limestone a few feet in thickness, not exceeding 20. It extends apparently the whole length of the Mesabi range, but has been identified in two places only, sec. 7, T. 58 N., R. 17 W., and doubtfully on the shores of Gunflint Lake. This limestone may be regarded as the basal horizon of the next overlying rock.

The black slate is probably several thousand feet in thickness and constitutes the bulk of the Animikie. In the neighborhood of Gunflint Lake it has been divided by Dr. Grant into a lower black-slate division and an upper graywacke-slate division, both of which members are intruded by diabase sills

In the Indian reservation at Grand Portage and at various places along the Grand Portage trail is a graywacke, which is supposed to overlie the black-slate member, but its extent and stratigraphic position have not been satisfactorily established.

The top of the Animikie has not been identified. The first recognizable datum plane after the close of the Animikie is the Puckwunge conglomerate, supposed to be the fragmental base of the Keweenawan.

At one or two places southwestward from Birch Lake, and at Little Falls on the Mississippi River, and in Morrison County, the Animikie has been converted into a mica-schist.

The age of the Animikie is believed to be Lower Cambrian for the following reasons: It graduates upward into Upper Cambrian rocks as seen on the south side of Lake Superior. The derivation of the iron ores from a glauconitic greensand indicates that large quantities of foraminiferal organisms once lived in the Animikie ocean, and Matthew has shown the existence of foraminiferal organisms associated with the iron ore in the St. Johns group of New Brunswick. Further, the Animikie has a uniformly low dip, while the lower strata are all highly tilted. There must therefore have been a great lapse of time between the deposition of the two series.

The Keweenawan.—The Puckwunge conglomerate is taken to be the fragmental base of the Keweenawan, although certain igneous rocks which antedate it, and which, perhaps, are contemporaneous with the upper portions of the Animikie, are also called Keweenawan. The conglomerate is found at Grand Portage Island, at Isle Royale, on the Baptism River, at Little Marais, on Manitou River, at the deep well at Short Line Park, near Duluth, and at New Ulm.

Above this conglomerate are conglomerates and sandstones of Keweenawan age which are stratified with lavas of diabasic nature. Still higher up the eruptive rocks become less in quantity and the fragmental rock is a sandstone, known as the Hinckley sandstone, quarried in the gorge of the Kettle River in Pine County. This in turn grades up into typical Upper Cambrian sandstones of the St. Croix Valley. The term Potsdam is restricted to the Puckwunge conglomerate and the hardened quartzites immediately overlying it, represented by the Sioux quartzite, the Baraboo and Barron county quartzites of Wisconsin, the quartzite at Grand Portage Island, and west of Grand Portage village, the New Ulm quartzite in Cottonwood County, and the quartzite in Pipestone County.

The igneous rocks of the Keweenawan vary in age from the late Animikie time to the top of the Keweenawan series. They are divided into two groups, the Cabotian or Lower Keweenawan, and the Manitou or Upper Keweenawan.

The Cabotian division includes gabbro and contemporaneous red rock and their surface lavas, and all other dikes and sills which are associated with, but younger than, the Animikie clastic rocks, and which are older than the Puckwunge conglomerate. The lower member of the Cabotian is the gabbro, which covers an enormous area. It extends on the east to East Greenwood Lake, in T. 64 N., R. 2 W. On the north it is bounded by the Animikie strata of the Mesabi iron range. Its westernmost exposure is in the vicinity of Short Line Park, Duluth. The southern limit is irregular, swinging from East Greenwood Lake in a zigzag manner through T. 63 N., R. 1 W.; T. 62 N., R. 2 W.; T. 62 N , R. 4 W.; T. 60 N., R. 6 W.; T. 60 N., R. 7 W.; T. 58 N., R. 10 W.; and T. 55 N., R. 11 W., to Duluth.

Along the northern and northwestern side of the Great gabbro mass, the gabbro is plainly intrusive on the older formations, Animikie and Keewatin.

From the northern border of the gabbro many sills offshoot and penetrate the Animikie strata parallel to the bedding. These are known as the Logan sills.

Near its contact with the underlying rocks, both the Animikie and Keewatin series, there are various altered rocks which can be connected in places with the gabbro and in places with the underlying rocks. To these altered rocks the term muscovadyte has been applied. It includes the various so-called peripheral phases of the gabbro.

On the southern and eastern border the gabbro is penetrated by and penetrates in a confused manner the red rock, with which it alternates both structurally and areally. It is believed to have resulted from the metamorphism by the gabbro of the Animikie, and perhaps earlier fragmentals.

As the granites of the Archean are believed to have resulted from the softening of acid fragmentals, so the gabbro may probably have been the result of the metamorphism or refusion of the Keewatin greenstones.

The anorthosite masses of the Beaver Bay diabase, supposed by Lawson to be Archean and to underlie unconformably the Beaver Bay diabase, are believed to represent segregation phases in the main gabbro flow, and to be the same as anorthosite masses in the gabbro proper to the west.

The Beaver Bay diabase is believed to represent the upper portion of the Great gabbro flow, and to be due to the first and greatest movement of the gabbro toward Lake Superior. The Logan sills belong to this part of the gabbro flow.

The Manitou division of the Keweenawan includes the surface flows, sills, and dikes which accompanied and followed the Puckwunge conglomerate. These eruptives, with the clastics associated with them, do not have a thickness in Minnesota of more than 1,000 feet. These lava sheets extend along the shore of Lake Superior from near Baptism River to near Grand Marais, except where replaced at intervals by the Beaver Bay diabase or some of the intersheeted fragmentals. They occur also in the neighborhood of Grand Portage Bay, but their extent here is not definitely known.

General.—The most important petrologic conclusions reached from the examination of the Minnesota crystalline rocks are three in number:

1. All the granites of the Archean can be explained on the assumption that they are intrusives representing the metamorphosed conditions of clastic rocks adjacent to the observed intrusions, rendered plastic by the force of dynamic metamorphism accompanied by moisture.

2. The Keweenawan gabbro and its derivatives are derived from the metamorphism and refusion of the Archean greenstones and their attendants.

Comment.—The two main petrologic conclusions announced by Professor Winchell as the most important results of his final petrologic work, summarized in the closing general paragraph, would be dissented from by most of the other geologists who have worked in this area.[a]

The Cambrian age of the Animikie strata has long been maintained by Professor Winchell, and above are summarized his arguments in support of this position. The first argument, that the Animikie grades into the Upper Cambrian rocks, is not in accord with the observations of most of the geologists above referred to. The second argument, based on the similarity of the unaltered greensand in the Mesabi district to that in the Cambrian of the eastern United States, loses weight when we consider the fact that the similarity is not great, the differences being many and significant;

[a] Some of these geologists are: R. D. Irving, C. R. Van Hise, J. Morgan Clements, W. S. Bayley, U. S. Grant, J. E. Spurr, A. H. Elftman, C. K. Leith.

and if the similarity were complete, the correlation would involve laying too much stress on lithologic similarity of widely separated formations. Professor Winchell's latest conclusion, that the Mesabi greensand is volcanic and not organic, while entirely dissented from by others who have studied this rock, in itself spoils his argument based on similarity. The third argument in favor of the Cambrian age of the Animikie, based on the extent of the unconformity beneath the Animikie, has little value when unsupported by the other lines of evidence. Professor Winchell's conclusion as to the Cambrian age of the Animikie strata is thus not adequately sustained by the reasons given. The view that the Animikie is Upper Huronian (pre-Cambrian) is the commonly accepted one. The evidence favoring this view is summarized by Van Hise.[a]

Further comment on the above work would require reference to the detailed observations made in northeastern Minnesota during four years by the Lake Superior Division of the United States Geological Survey. The results of this work are published in this monograph. In general it may be stated that now, as in the past, there is a divergence in the conclusions reached by the Minnesota survey and by the United States Geological Survey concerning the position and importance of the unconformities, the correlation of series, and the nomenclature.

1900.

Coleman, A. P. Copper and iron regions of Ontario; with Report of the Ontario Bureau of Mines, 1900, pp. 143–191.

This paper deals incidentally with the Vermilion district (pp. 150–154). Before the regular field work was begun in Ontario the author, accompanied by Prof. Arthur B. Willmott, visited the Lake Superior iron ranges of the United States. The Vermilion range was visited, among others, and a few desultory observations concerning the mines and rocks in the vicinity of the mines are recorded.

Grant, U. S. Contact metamorphism of a basic igneous rock: Bull. Geol. Soc. Am., Vol. 11, 1900, pp. 503–510.

Along the northern edge of the Great gabbro mass of northeastern Minnesota there occur certain peculiar crystalline rocks. These have been produced by the contact action of the gabbro on rocks of varied lithologic

[a] Correlation Papers, Archean and Algonkian, Bull. U. S. Geol. Survey No. 86; Principles of pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, Pt. I, 1896, pp. 571–874.

character. It is the object of the paper to give in outline an account of the phenomena seen on these rocks. An outline of the local geology is given. The rocks range from Archean, through the Lower Huronian (or Keewatin) and Upper Huronian (or Animikie), to the Keweenawan. The Animikie of this area is subdivided from the base up into an iron-bearing member, a black-slate member, and a graywacke-slate member. The Keweenawan is represented by the gabbro, which has metamorphosed the Gunflint iron-bearing beds, and the graywacke and black slate members of Upper Huronian age.

The metamorphism of the black-slate and graywacke-slate members is relatively insignificant, and consists of the more or less complete recrystallization of the rocks, which are now made up of granitic aggregates of quartz, feldspar, biotite, muscovite, and occasionally cordierite.

The most complete recrystallization and the most interesting phenomena are shown in the metamorphosed iron-bearing beds.

The original rock is regarded as a glauconitic greensand in which there is more or less iron carbonate. This has been altered to a quartz-magnetite-amphibole-slate, the amphibole being in the form of actinolite, grünerite, cummingtonite, and hornblende. This has been profoundly changed by the gabbro, and is now a coarse-grained aggregate of quartz, magnetite, olivine (which is frequently fayalite), hypersthene, augite, hornblende, and occasionally grünerite and cummingtonite. These rocks, like the rocks from which they are derived, are beautifully banded, the separate bands being composed of quartz, or of magnetite, or of silicates, or of a mixture of any two or more of the minerals.

Satisfactory reasons are given showing that these rocks are a part of the Animikie (Upper Huronian) and not a border facies of the gabbro, as has been thought to be the case by some.

The gabbro is in contact with very diverse strata of the Keewatin, and the resulting metamorphic rocks differ greatly. Biotite and hypersthene are prominent in these contact rocks.

The Archean consists of granites and greenstones. The granites have not been affected by the gabbro in a noticeable way at least. The greenstones have been affected in such a way as to reproduce the minerals of the original rocks from which the greenstones were derived. Commonly a granular product is found which is quite similar in appearance to a gabbro.

Comments.—The members of the United States Geological Survey who have been studying this area place the dividing lines in some cases at places somewhat different from those where Grant places them. They make the same main divisions, however. The glauconitic greensand of Grant is now known not to contain potassium, the green granules being composed of a hydrous ferrous silicate.[a]

The United States geologists concur in the general conclusions reached by Grant as to the character and cause of the metamorphism.

1901.

WINCHELL, N. H. The geology of Minnesota: Final Report Geol. and Nat. Hist. Survey of Minn., Vol. VI, 1901. Geological atlas with synoptical descriptions, 88 plates.

This is a collection of maps of Minnesota. The earlier ones, from Franquelin's map of 1688 up to and including Nicollet's of 1842, are reproduced, and then the later maps published by the Geological and Natural History Survey in the reports preceding this. Brief explanatory notes accompany each plate.

WINCHELL, N. H. Glacial lakes of Minnesota: Bull. Geol. Soc. Am., Vol. XII, 1901, pp. 109–128, pl. 12.

Winchell gives a brief description of a number of glacial lakes occurring in Minnesota. Among these there are two, Lake Norwood and Lake Onnamani, which lie partially or wholly in the Vermilion district.

VAN HISE, C. R. The iron-ore deposits of the Lake Superior region: Twenty-first Ann. Rept. U. S. Geol. Survey, Pt. III, 1901, pp. 305–434, 12 plates, 6 of which are geological maps.

This paper contains a brief description and comparison of the various iron-bearing districts of the Lake Superior region.

The first chapter contains a general discussion of principles. The rocks of the region, disregarding the late formations, are stated to be divisible into the following five series, enumerated from base up: Archean, Lower Huronian, Upper Huronian, Keweenawan, and Cambrian.

The chief varieties of the iron-bearing rocks and their alterations are described. They are shown to occur in the three series, the Archean, Lower

[a] The Mesabi iron-bearing district of Minnesota, by C. K. Leith: Mon. U. S. Geol. Survey Vol. XLIII, 1903, pp. 110.

Huronian, and Upper Huronian. The genesis of the ore deposits is then discussed.

The general process of ore formation for the Lake Superior region as a whole is the same as that already described in the monographs on the Penokee and Marquette districts. The iron is leached from an older formation—in case of the Archean from igneous rocks, the greenstones—and is then deposited as a sedimentary formation, in the form of a cherty carbonate or some iron compound, which, however, becomes this cherty carbonate. These formations are folded and intruded by igneous rocks, and pitching troughs with relatively impervious sides and bottom are formed. Meteoric waters carry downward in solution iron derived from the iron-bearing formation, and this is precipitated as an oxide in the structural basins in the formation and in the spaces left by removal of the silica. As result of this replacement, enrichment of the iron-bearing formation occurs at favorable places, and the ore deposits are formed.

Sections are devoted to a consideration of the influence of topography and denudation on ore deposition, and to a discussion of the time and depth of concentration of the ore deposits.

In Chapter II the individual districts are taken up. The section devoted to the Vermilion district is written by Van Hise and Clements, and in this is given the first detailed statement made by the United States Geological Survey on this district. A preliminary map accompanies the description. Since this section on the Vermilion district is in fact a very brief abstract of the present monograph, it will not be reviewed in detail. It may be well to mention the fact that the Archean is here made to include certain sedimentary rocks In the last chapter, the third, there is a comparison and summary of all the districts. The Vermilion district is again briefly considered, and some suggestions are offered in regard to exploration in it.

CHAPTER III.

THE ARCHEAN.

SECTION I.—DEFINITION AND SUBDIVISIONS.

The Archean, as heretofore defined by Professor Van Hise, was made to include all pre-Algonkian rocks, and these were supposed to be igneous rocks only.[a] As a result of the work of the field season of 1900 on the north shore of Lake Superior in Minnesota and Canada, it has been found necessary to modify our ideas of the Archean and to change the definition of the word accordingly. The term Archean, as used in the present paper, comprises rocks older than the Algonkian, which are predominantly of igneous origin, but with which may be included some subordinate amounts of sediments.

From the study of the Vermilion district it has been found possible to divide the Archean of that district into three stratigraphic divisions, which, enumerated in order of age, beginning with the lowest, are: Ely greenstone, Soudan formation, and a series of granitic rocks. The Ely greenstone consists of basic to intermediate igneous rocks, and is the lowest member of the geologic column in this district. Above this occurs an iron-bearing formation, the Soudan formation, of totally different lithologic character and mode of origin, whose base is marked here and there by a conglomerate of small extent. The iron-bearing formation is followed by a series of acid intrusives varying from rhyolite-porphyries to granites and granite-porphyries, with normal granites as the predominant form. These rocks show in many places their intrusive relationship to both of the earlier formations. These three formations constitute the Archean and are sepa-

[a] Correlation papers—Archean and Algonkian: Bull. U. S. Geol. Survey No. 86, 1892, pp. 156–199. Also Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Pt. I, 1896, pp. 581–872.

rated from the next succeeding series by a great unconformity. The formations will be taken up in order of age and described separately in the following pages.

SECTION II.—ELY GREENSTONE.

FEATURES OF THE GREENSTONE.

In the Vermilion district there is a great complex of igneous rocks whose members possess one general character in common. They are almost universally colored some shade of green; hence, for want of a better one, the descriptive term "greenstone" is applied to the complex. To judge from microscopic examination, no chemical analyses having been made, the rocks constituting this complex vary in chemical character from intermediate to basic rocks. They likewise possess varied physical characters. The various parts of this complex are not of exactly the same age, as in a number of places one member of the complex intrudes other members; nor are the rocks all of exactly the same mode of origin, as some are effusive and others intrusive, although all are igneous. These differences in age and mode of formation are, however, only such as we normally expect to find in rocks belonging, as these do, to one great period of eruptive activity which certainly extended over a great length of time.

Finally, a number of patches of fragmental rock are found in the midst of the Ely greenstones. These patches are too small to be shown on the accompanying maps. Moreover, it is still doubtful whether these are tuffs contemporaneous with and interbedded with the flows, or normal conglomerates derived from the greenstones and infolded in them. It is probable that both of these rocks are present, but owing to the imperfect exposures it was impossible to distinguish them.

As a unit the Ely greenstones bear the following general relations to the rest of the rocks of the district. They are in all cases older than the other rocks. From them have been largely derived the later clastics and upon them rest all of the sediments. Through them have been intruded all of the remaining igneous rocks. The Ely greenstones are all Archean, or, if a more general term is desired, they form the basement complex of the Vermilion district. This complex is very well developed in the immediate vicinity of Ely, the largest city of the district, which is literally built upon a firm foundation of these greenstones, and the complex shows some of its most typical and interesting characters right in the streets and lots of the city. For this reason the formation has been appropriately called the "Ely greenstone."[a]

OCCURRENCE AND CHARACTER.

DISTRIBUTION.

In the westernmost part of the district, in the vicinity of Vermilion Lake, the area underlain by the greenstones has the form of a number of large westward-projecting tongues. Beginning their enumeration from south to north we find the first large tongue extending through the northern portion of T. 61 N., R. 15 W. North of this there is another tongue, in secs. 35 and 36, T. 62 N., R. 15 W. This is followed to the north by a third tongue, in secs. 24, 25, and 26, of the same township and range. A number of very small tongues are to be found in the northern portion of sec. 21, T. 62 N., R. 14 W. A very narrow greenstone belt extends to the southern portion of secs. 15, 16, 17, and 18, T. 62 N., R. 14 W. Still another such tongue is in sec. 12, T. 62 N., R. 15 W., and extends, except in one small area, eastward through secs. 7, 8, and 9, T. 62 N., R. 15 W. Still farther north we find a tongue south of Bass Lake, in secs. 1, 2, 3, and 4, T. 62 N., R. 15 W., and one immediately north of this, just along the line between T. 62 N., and T. 63 N. The northern side of Vermilion Lake is bordered by this Archean greenstone, which has been followed out to the west to the limit of the area mapped. The greenstone extends a long distance to the west of the Vermilion district, although it is discontinuous over great areas. While it may be that this interruption of the continuity of the greenstone in this portion of the State is due to its concealment in places by overlying drift, it is also highly probable that even were this drift removed we should find that the continuation of the greenstone is interrupted, as it is in the vicinity of Vermilion Lake, by the overlapping of the younger formations.

In all cases these tongues, when followed out to the east, unite with the main mass of the Archean which, along the line between Rs. 13 and

[a] The term "Kawishiwin" has been proposed by the Minnesota survey (Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, pp. 270–271 and 546) to comprise the two formations which in this volume are treated under the terms the "Ely greenstone" and the "Soudan formation," as well as certain other rocks. Since this throws together two important formations that are here treated separately, it has seemed necessary to introduce new names for each of these.

14 W., covers almost the entire central portion of the district and has there an approximate width of 10 miles. This great width of the Ely greenstone continues to the east very nearly as far as Pine Lake, in R. 10 W. Within this area its continuity is interrupted in a number of places by narrow belts of sediments of later age trending approximately east to east-northeast. These, although of minor importance so far as areal distribution is concerned, are of great economic importance, as within the area just described they consist for the most part of the iron-bearing formation. About 7 miles west of Ely, in sec. 4, T. 62 N., R. 13 W., begins a series of sedimentary rocks which splits the Ely greenstone approximately in the center. This belt of sedimentary rocks continues on to the east with approximately uniform width beyond the end of Fall Lake, in sec. 31, T. 64 N., R. 10 W., where it ends. Just about three-quarters of a mile beyond this there begins another belt of sediments which continues eastward, widening very rapidly, and corresponding to this widening there is a rapid reduction in the width of the greenstone areas lying north and south of it. The northern belt of greenstone narrows more rapidly and disappears north of Moose Lake, in sec. 16, T. 64 N., R. 9 W., where it is covered by overlapping sediments. The continuation of this belt is wanting for a distance of about a mile. It then begins again in sec. 10, T. 64 N., R. 9 W., and continues thence northeast to the international boundary.

From here on to the northeast the extension of the Ely greenstone has been traced into Canada as the result of a reconnaissance survey. The boundaries of the formation in Canada, as given upon the accompanying maps, can not, therefore, be regarded as nearly so correct as those given within the United States. They have been found in most places as a result of the study of exposures along the lakes and of a few traverses inland. This reconnaissance shows us that the width of the Ely greenstone, as it continues to the northeast, varies greatly as a result of the folding to which it has been subjected. As a result of this, also, its continuity is interrupted by the infolding of the younger rocks whose areas have been delimited. Upon the map it appears to cover a larger area than it does in reality, for the reason that the important iron-bearing formation has not been delimited, although its presence within the greenstone area is known from its having been observed at a great number of places.

Returning to the southern arm of the greenstone, we find it covering the major portion of T. 63 N., R. 10 W., with a small portion of T. 64 N. As we follow it eastward into T. 63 and T. 64 N., R. 9 W., we find that its width is materially reduced. This results from the fact that in this area we are upon a great anticline plunging to the east, around which wrap the younger formations. These are likewise infolded in synclines within the greenstone, as is to be expected, for instance, in sec. 17, T. 63 N., R. 9 W. In the southern portion of T. 64 N., R. 9 W., this infolding is beautifully shown. As a result of this the greenstone is divided into a number of narrow belts having, in general, an east-west trend, each belt being separated from every other, and from the main mass of the greenstone to the south, by a trough containing later sedimentary deposits. As results of cross folding the greenstone occurs in a number of places in anticlinal boss-like areas plunging down under the sediments and completely surrounded by them.

From the center of R. 9 W. eastward this greenstone is totally wanting until we reach the center of R. 8 W., where another anticlinal area of greenstone is found. This is surrounded on three sides by overlapping sedimentaries, the fourth, the eastern side, being cut off by the gabbro. As we go farther east we find that the greenstone is not continuous over any very broad areas. It occurs for the most part in rather narrow, long belts; for instance, such a belt begins on the point projecting westward into Knife Lake in sec. 21, T. 65 N., R. 7 W., and extends thence eastward into sec. 11, T. 65 N., R. 6 W., with a maximum width of about one-half mile. Alongside this belt, however, there are small isolated bosses surrounded by the younger rocks, as may be seen in the southwest quarter of sec. 17 and the southeast quarter of sec. 18, T. 65 N., R. 6 W. Similar greenstone areas occur south of Knife Lake in secs. 29, 30, and 31, T. 65 N., R. 6 W., and in secs. 25 and 36, T. 65 N., R. 7 W., and other small areas occur also in secs. 25, 26, and 27, T. 65 N, R. 6 W. Considerably larger is the greenstone massive forming the ridge upon which the Twin Peaks are prominent points, extending along the line between Ts. 64 and 65 N. eastward to Gobbemichigamma Lake. Still larger is the area that extends over secs. 18 and 19, T. 65 N., R. 6 W., eastward to sec. 27, T. 65 N., R. 4 W., having an east-west length of approximately 10 miles. This last belt starts in at the west with two westward-plunging anticlinal tongues separated by sedimentary formations, and, after varying materially in width as the result of cross folding, finally ends at its eastern extremity also in two tongues—eastward-plunging anticlines partially surrounded by the younger sediments.

EXPOSURES.

The exposures of greenstone in the areas outlined above are very good. It is no uncommon thing to find almost absolutely bare surfaces several hundred feet long and possibly one-fourth as wide. Such exposures are most commonly rounded surfaces. Occasionally, however, cliffs of greenstone are seen. In spite of the large size and the great number of the exposures, it was very difficult—in fact, in most places almost impossible—to determine the relations of the different kinds of greenstone to one another, for the contacts have usually been concealed either by drift or by the effects of erosion, so that where most needed, as is commonly the case, the exposures are wanting. Mention will be made later of a few places where some of the best exposures were found.

TOPOGRAPHY.

In the western portion of the district, where the the greenstone underlies broad areas, the topography is very much broken. The minor ridges are numerous and form the most prominent feature. In this portion of the district there is a series of parallel ridges with narrow valleys between them. Usually the sides have a steep slope, and there are sometimes abrupt escarpments, but as a rule the hills and ridges are well rounded. It will thus be seen that in detail the topography is very rugged. Especially is this so north of Fall and Long lakes. The ridges throughout the greenstone area lie in essentially parallel chains extending east-northeast, a direction corresponding to the trend of the structure of the district. It has already been stated that the Ely greenstone occurs very rarely in broad areas in the eastern portion of the district, being there usually found in comparatively small areas surrounded by younger sediments. There is a very noticeable difference in the topography of areas underlain by the greenstone and those underlain by the surrounding sediments, due to differential erosion. As a rule, the greenstone forms the prominent hills and main ridges. Usually, in traversing the country, one finds that after leaving the sediments, which lie within a topographic depression, there follow the low, rounded knobs or ridges of the greenstone. After passing over these and ascending a gentle slope the top is reached, which is usually a broad, flat dome. The descent on the other side carries one over similar topography, with the topographic break intervening in most cases between the greenstone and the sediments. In these large ridges the minor details of the topography are usually not very strongly accentuated, but in each case blend in the main ridge which, while forming a very marked topographic feature, is in general not separated into distinct peaks.

STRUCTURE.

In view of the essentially homogeneous, igneous character of the Ely greenstone, it will be readily seen that the geologic structure of the greenstones areas could not have been determined without the aid of the younger sedimentary formations. As the result of the study of the district, we find that the greenstones have been intricately folded, the folds have in many instances been carefully traced, and it has been found that in general the greenstone has been folded into a great synclinorium. The character of this is better brought out in the western than in the eastern part of the district. Within this synclinorium the synclines are occupied by the younger rocks, whereas the anticlines are of greenstone projecting through sediments of younger age. Typical anticlines of the greenstone, partially surrounded by the sedimentaries, occur in the vicinity of Vermilion Lake, in the western part of the district and are enumerated on page 432. Attention is here again called to the possibility that the greenstones reported to occur west of that part of the district mapped are perhaps the crest of greenstone anticlines projecting through the drift. The rocks of the Vermilion district have been affected by a second system of folds lying approximately at right angles to those that form the great east-west trending synclinorium. The effect of this cross folding is best shown by the steeply plunging anticlines and synclines in the sediments of later age, as well as by the distribution of the formations in general. If we examine the map including the area near the west end of Moose Lake, we find that as a result of the main folding the greenstone has been divided into a number of narrow belts separated from one another north and south by still narrower belts of sediments lying in synclines between the greenstones. It will be noted, also, that some of these belts are completely isolated and that others have but slight connection.

The isolation of the belts is due to the effect of the cross folding which has produced anticlines of greenstone plunging down under sediments that wrap around them. The most striking cases of these isolated anticlines are those shown by the distribution of the greenstone in the vicinity of Knife and Cacaquabic lakes and between Ogishke Muncie and Gobbemichigamma lakes. Looking at the distribution of the greenstone proper, we see that the presence of the synclinal structure is most marked in the western part of the district where the younger formations are infolded into the greenstone and where the greenstone predominates. In the eastern part of the district, on the other hand, the anticlinal structure of the greenstone is most marked for the reason that the minor synclines are very deeply buried by the sedimentaries, which have a great surficial extent, as a result of which only the crests of the anticlines are exposed where they project through the sedimentaries.

PETROGRAPHIC CHARACTERS.

The rocks comprised in the Ely greenstone originally corresponded in character to intermediate andesites and basic basalts and, like the recent representatives of these families, must have been black or dark gray, and presumably likewise corresponded to them in mineralogic character. These Archean rocks have undergone for so long a period the vicissitudes to which all rocks are exposed that it is not to be wondered at that they have for the most part been exceedingly altered and never show all of their original characters. Indeed, it is surprising that they retain any of their original structures. Most of the changes which have affected them have been in the character of the minerals, and these will be described in the proper place. The changes that are most obvious macroscopically are the chemical ones which have affected their color and the mechanical ones which have affected their structure.

While the rocks, on the whole, are of a greenish color (hence the general name of greenstone), the various phases of them show all possible variants of this, ranging from very light-colored greenish gray to very dark greenish black, with the light grayish and brownish greens predominating. The rocks appear lighter on the weathered surface, as a rule, than upon fresh fracture surfaces. Some of the greenstones are very much more feldspathic than usual, and in such cases they weather with a light-pinkish crust, which causes them not uncommonly to be mistaken, when viewed from a distance, for the more acid granites. The macroscopic textures commonly seen are the ophitic, the poikilitic, and the porphyritic. The rocks possessing these textures vary from fine-grained. almost aphanitic, ones to those which are very coarse grained and, in exceptional cases, have some constituents an inch and a half in length. The porphyritic rocks have as phenocrysts feldspar or hornblende, or both, in a matrix which varies from fine to coarse in grain. Some of the feldspar phenocrysts are an inch and a half in length. Many of the finer grained forms of these rocks are amygdaloidal and also frequently show beautiful cases of spherulitic development.

Good columnar parting is totally wanting in the greenstones of the Vermilion district, but, apparently taking its place, ellipsoidal parting[a] is abundantly present. All combinations of the above structures and textures may be found in this complex and all gradations between the rocks possessing them. Thus we find gradations from fine to coarse forms and from the nonporphyritic to the porphyritic. Those that are not amygdaloidal at one place may become amygdaloidal elsewhere, and with this change we may find the rocks becoming porphyritic, possibly showing ellipsoidal parting. Fine-grained ellipsoidal and spherulitic basalts grade into coarse-grained ellipsoidal spherulitic basalts, or into coarse-grained basalts that are neither ellipsoidal nor spherulitic.

The greenstones are predominantly massive. Nevertheless they show the effect of dynamic action and are in many cases finely jointed. The dynamic action affecting them has resulted in the production in several places of very excellent friction breccias (reibungs-breccias) which can with difficulty be separated from tuffaceous or conglomeratic deposits. On the bare hills south of Moose Lake these basalts are in places brecciated, producing rocks that strikingly simulate greenstone conglomerates. In most cases the brecciated zone has a width of only a few feet. These breccias might readily be mistaken for true conglomerates if the adjacent massive rocks were covered and the breccias only were exposed. The ellipsoids on great numbers of the exposures have very numerous and prominent gashes which traverse them at various angles, though usually nearly at right angles to the direction of elongation. These are clearly indicative of the mashing to which these ellipsoids have been subjected.

---

[a] Mon. U. S. Geol. Survey Vol. XXXVI, 1899, pp. 112–124.

The mashing of the Ely greenstone has resulted in producing very commonly an imperfect schistose structure in the rocks composing it. In exceptional cases and locally this development of schistosity has advanced to such a point that the rocks have become completely schistose, and even finely fissile. Gradations from the massive, coarse-grained greenstones to green schists of dynamic origin have been observed in a number of places. This schistose structure has, however, certainly not reached such universal development that one would be warranted in speaking of the Ely greenstone as a green schist complex.

Finally, there occurs in a number of places with the rocks described a conglomerate or tuff, whose structural relations to the greenstones are somewhat doubtful. This facies is found commonly in small and isolated exposures or under other conditions that preclude the determination of its relationship to the nearest greenstones. These rocks consist of more or less rounded but irregularly shaped fragments of greenstones of various kinds, but corresponding to those that occur all around them in the district. One can not say, however, that these deposits consist chiefly of fragments of greenstones like those that are nearest them. No definite indications of bedding have in any case been found, nor do the rocks occur in connection with any sediments of which they can be the basal conglomerates. In some places they lie between exposures of the massive greenstone, and one is inclined to interpret such a field relationship as due to alternation of flows and tuff deposits. On the other hand, however, one may readily interpret this relation as due to infolding of the clastics in the greenstones. Rocks very similar to these, but showing the transition to finer-grained, clearly sedimentary deposits have been found in several places, and are described with the Soudan formation, to which they belong. The latter deposits clearly owe their field relationship to infolding within the greenstones. It is highly probable that most, if not all, of these conglomeratic rocks should be so classed. However, a few cases, which will be mentioned under the heading "Interesting localities," have been doubtfully referred as tuffs to the Ely greenstone. These clastics have nothing to do with those belonging to the Ogishke conglomerate, which will be subsequently considered.

In numerous places the altered greenstones have been more or less thoroughly discolored and impregnated with iron. This impregnation is, in all of the cases observed, almost purely superficial, extending at most only a few feet down into the rocks. Such occurrences have led to considerable waste of money in the sinking of prospect holes. The joints and gashes in numerous places throughout the district have been found filled more or less completely with quartz, occurring both as vein quartz and in a saccharoidal condition, more or less intimately mixed with carbonates. In several places large veins of quartz traverse the greenstones, but minute ones are more common. The largest veins have been prospected for gold, and several gold mines, so called, have been opened along them. Where the quartz veins are mixed with carbonates the carbonate usually carries a considerable content of iron, so that on weathered surfaces such vein deposits are quite ferruginous. This infiltrated carbonate-bearing material[a] is especially common in the interstices and in the schistose matrix between the ellipsoids. In this same position, and apparently but a further alteration product of such secondary carbonate-bearing deposits, is a white, black, or purplish chert, and less frequently a red jasper. Not uncommonly, also, the non-ellipsoidal greenstone near the jasper belts contains irregular bunches and lenticular areas, varying in size, of rather coarse white and black chert, with more rarely the true red jasper. Such deposits are certainly, in many cases, composed of infiltration products brought from overlying formations and deposited in the interstices of the basal greenstones. They are never of very large size, and it is of course useless to prospect in such places for paying ore bodies.

Certain of the macroscopic structures, namely, the amygdaloidal, the spherulitic, and the ellipsoidal, mentioned above as being present in these greenstones, are very well developed, and on account of this, but chiefly as they offer a clew to the mode of formation of the greenstones, they are of some interest and will be described in detail.

THE AMYGDALOIDAL STRUCTURE.

Of the three structures mentioned above the most common is the amygdaloidal. This is rarely seen in the very coarse greenstones, but is usually present in the finer-grained varieties. This structure is most noticeable on weathered surfaces, where it may be recognized by the presence of rounded or oval spots scattered over the rock. On examining the internal

[a] Mon. U. S. Geol. Survey Vol. XXXVI, 1899, pp. 130–135.

structure of the greenstone, one sees that these spots, which are also scattered through the body of the rock, are frequently cross sections of irregular tubes lying perpendicular to the surface of the flow. They are sections through filled gas pores, the filling being known as amygdules. The amygdules consist of chlorite, calcite, quartz, actinolite, and epidote. Rarely is any one of the minerals absolutely alone in the amygdule, though usually one or the other will greatly predominate. The amygdules are filled with chlorite; chlorite and quartz; calcite; chlorite and calcite; chlorite and epidote; chlorite and actinolite; chlorite, calcite, and quartz; calcite and quartz; and quartz alone. The materials constituting these amygdules are arranged above in approximately the order of abundance. According to whether the light or the dark minerals predominate, we get light-colored to white granular areas on the one hand, grading to light-greenish to silky dark-green areas on the other. The gas pores of these rocks owe their origin, as has already been hinted at, to the pressure of the gas in an originally molten magma. When this magma reached a position where the pressure was markedly diminished, the gas separated, segregated, and expanded, and the magma became more scoriaceous on the surface; and the pores are found to diminish in number and size as those portions of the original molten magma that were under greater and greater pressure are reached. A concomitant of the formation of the gas pores is the relatively rapid cooling of the magma, producing rocks of a glassy nature or of very fine grain. Both of these conditions commonly confront us in volcanic rocks or, in other words, in rocks that have overflowed upon the surface. It is true that amygdules have been observed in rocks which occur clearly as sills and dikes, and which therefore never actually reached the surface in a molten condition. These cases are, however, relatively rare, and one can readily see that the enormous reduction of pressure occasioned by the intrusion of the sills into their present places from much lower positions would readily permit the expansion of the included gas. Moreover, in such cases amygdules are far from numerous, showing that the pressure was diminished to such extent that relatively few pores were formed. In the case of the amygdaloidal greenstones in the Vermilion district we observe the following conditions: First, almost universally when amygdules are present they occur in great quantity and are very commonly of large size; second, the amygdaloidal structure accompanies a fine-grained condition of the rock.

The combination of these two characters and their general distribution among the greenstones seem to indicate that these greenstones, in great measure at least, were poured forth at the surface.

THE SPHERULITIC STRUCTURE.

The Ely greenstones are very frequently marked by small, rounded, raised areas, which differ in color from the matrix, being either lighter or darker. They range in size from that of a pin's head up to 3 inches in diameter. No structure is visible on the very small areas. They merely stand out on the weathered surface of the rock as so many small nodules, their relief being the result of differential weathering. On the larger bodies, however, a distinctly radial arrangement can be seen, and this is especially well shown on weathered surfaces. The essential characteristic of spherulites is that they are formed of radiating or diverging groups of crystals which commenced to crystallize from one point or a center. These are the characteristics of the objects mentioned. They are similar in general characters to the spherulites of the acid lavas, but differ from them in mineralogic, and hence, of course, in chemical, composition. One can see with the naked eye that chlorite in radiating fibers is the chief constituent of some of the spherulites. Most of them are formed of a grayish material whose character can not be recognized macroscopically. The characters of these spherulites as seen under the microscope will be described below (see p. 152). From the published descriptions of various occurrences of spherulites it appears that they are generally found in rock masses that are believed to be flows, or, more rarely, upon the selvage of small dikes. So true is this that spherulites, like porous and slaggy structures, have come to be considered as fair evidence of the original extrusive character of rocks in which they occur. This spherulitic structure is not found, however, accompanying the amygdaloidal rocks in the Vermilion district. On the contrary, the conditions for the formation of gas pores in large quantity seem to have precluded the formation of spherulites, although some few vesicles may occur with the spherulites. On one good exposure a traverse showed the fine-grained amygdaloidal rock grading downward into a rock growing gradually coarser and coarser, in which the amygdules disappear, and when they had completely disappeared the spherulites were found to have developed in large quantity. These pre-Cambrian basic lavas exhibit conditions almost exactly the same as those observed by Iddings in the acid lavas of much more recent times in the Yellowstone Park and described by him as follows:[a]

> In recapitulation, then, this rhyolitic lava is a flow about 100 feet thick, except where it has piled up in a small valley. It is glassy, except the lithoidal portion in the valley, and is free from phenocrysts. The obsidian is dense in a lower part of the edge and carries numerous spherulites. Large vesicles occur in the upper portion, and toward the surface of the flow the spherulites disappear and the glass becomes filled with gas cavities and passes up into pumice. * * * These characteristics repeat themselves in the rhyolite in various parts of the park.

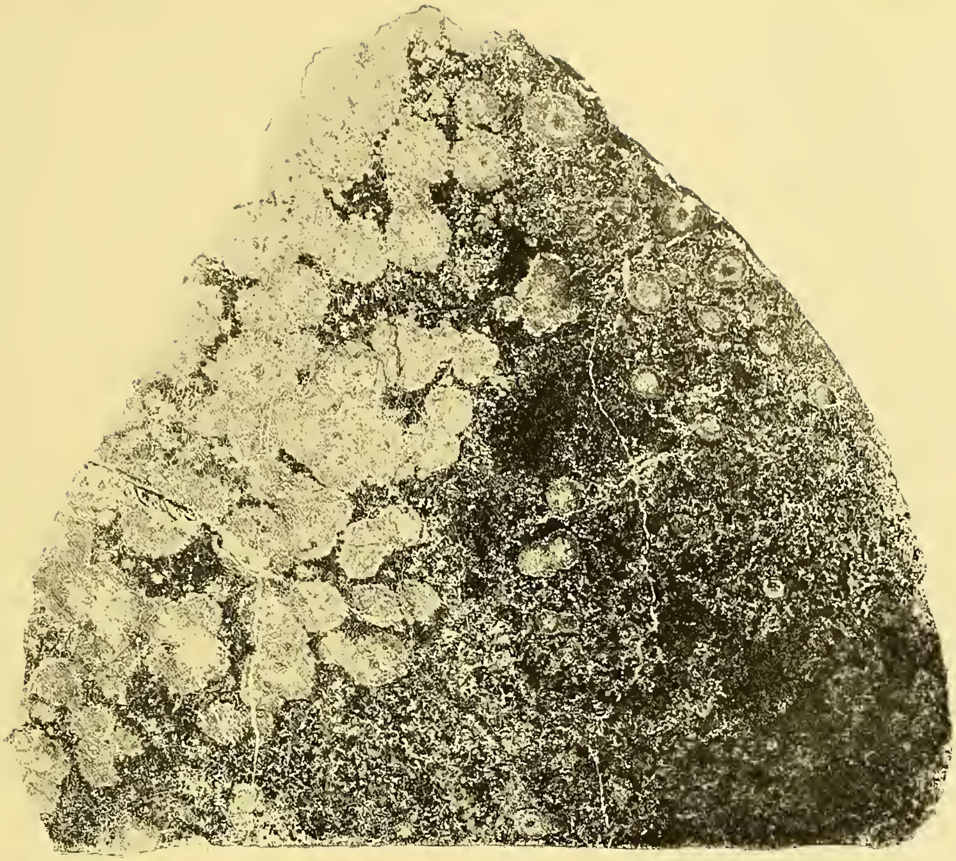
Up to the present time there have been, to my knowledge, only two occurrences of basic spherulites or spherulitic rocks (variolites) described from North America. The one was by Ransome from California[b] and the other by myself from the northern peninsula of Michigan.[c] In the case of the Ely greenstone the spherulitic structure is, as has already been intimated, one of the most common, most characteristic, and most striking features of the rock. The spherulitic greenstones are distributed in discontinuous exposures over a great number of square miles. For instance, they are very common and beautifully developed on the bare hills north of Long Lake in secs. 10, 11, 14, 15, 16, 21, and 22, T. 63 N., R. 12 W. They are especially common just southeast of Jasper Lake in secs. 1 and 12, T. 63 N., R. 10 W., and sec. 6, T. 63 N., R. 9 W. They are also very common west of North Twin Lake in secs. 10, 11, 14, and 15, T. 63 N., R. 10 W. Well-developed spherulites occur also about a mile north of North Twin Lake at the northeast corner of sec. 12, T. 63 N., R. 10 W. In many of the places mentioned, especially in sec. 6, T. 63 N., R. 9 W., the exposures are almost solid masses of spherulites, which show very beautifully on the weathered surface their radial structure. Figures *A* and *B* of Pl. III are illustrations made from a polished and a weathered specimen, respectively, of these spherulitic rocks, and give a correct idea of their appearance.

---

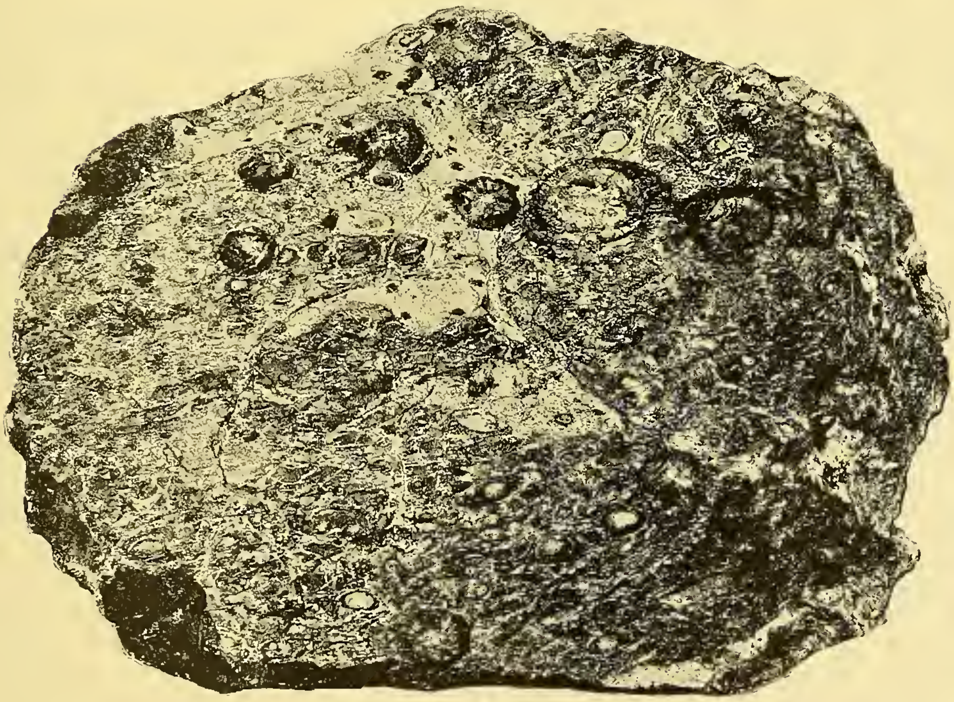
[a] Geology of the Yellowstone National Park, Descriptive Geology, Petrography, and Paleontology, by Hague, Iddings, Weed, Walcott, Girty, Stanton, and Knowlton: Mon. U. S. Geol. Survey Vol. XXXII, Part II, 1899, p. 365.

[b] The eruptive rocks of Point Bonita, by F. Leslie Ransome: Bull. Univ. of Cal., Vol. I, 1893, p. 99.

[c] The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey Vol. XXXVI, 1899, p. 108.



A.



B

SPHERULITIC TEXTURE IN THE GREENSTONES.

A. Fragment taken from the periphery of a spherulitic ellipsoid. The outside of the ellipsoid is made of the finest-grained material, with an occasional spherulite. Near the center the spherulites are more numerous and larger.

B. This illustrates the spherulitic character of many of the greenstones, especially those which show the ellipsoidal parting.

When the clearly recognizable characters of the spherulites, as shown in the above illustrations, and the extent of the distribution of these spherulitic greenstones are taken into consideration, it is with very great surprise that one finds that the only recognition which the spherulites have received was by N. H. Winchell, who states, in his report,[a] that the surface of the rock is mottled by small areas of lighter color than the matrix in which they lie, and refers to them as indicating an original amygdaloidal or fragmental structure. Spherulites are now known to exist in the ancient acid volcanics over various regions of the United States. They have also been described from numerous localities where more recent acid lavas are developed. Iddings well states the probable reason for the more frequent occurrence of such crystallizations in acid than in basic lavas in the following words:[b]

> The greater frequency of lamination and localized crystallization in acid lavas as compared with basic ones is a consequence of the generally greater viscosity of acid lavas at the time of their eruption. The basic rocks have a considerably lower melting point and are much more liquid up to the temperature of solidification. Hence, diffusion would take place more rapidly and the magna would be more homogeneous, other things being equal.

The spherulitic metabasalts or greenstones are extraordinarily abundant in the Vermilion district. They have a very great development in the adjacent portions of Ontario underlain by greenstones. The spherulitic structure occurs in similar Huronian rocks in the Crystal Falls district of Michigan, and is likewise developed in the rocks of the Menominee district of Michigan. Mr. C. K. Leith reports the occurrence of similar rocks in the Mesabi district of Minnesota. Considering the extraordinarily widespread development of this structure in the areas mentioned, one is led to wonder at the fact that it is not present in similar rocks which have a widespread occurrence in the Penokee-Gogebic district of Michigan and Wisconsin, and in the Marquette district of Michigan. Furthermore, it seems surprising that this structure should not exist in the somewhat more recent metabasalts of the Keweenawan of the Lake Superior region, and in the still more recent basalts of the Triassic of the Atlantic coast. It seems highly probable that this spherulitic structure must exist, at least

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV 1899, p. 253.

[b] Geology of the Yellowstone National Park; Descriptive Geology, Petrology, and Paleontology, by Hague, Iddings, and others: Mon. U. S. Geol. Survey Vol. XXXII, Part II, 1899, p. 425.

in a limited development, in the rocks of the areas mentioned, and that its occurrence has simply been overlooked, or else that the spherulites were not recognized as such, but were called amygdules, as they were in the notes of some of the observers in the Vermilion district before attention was called to the true character of these bodies.

THE ELLIPSOIDAL[a] STRUCTURE.

The ellipsoidal structure in pre-Cambrian greenstones (metabasalts) was described by the author in 1899,[b] and the attempt was made to account for its occurrence. It was concluded that the greenstones correspond in general characters and in mode of origin to aa lava, and that the ellipsoids were due to the breaking up of this relatively viscous lava. It was concluded that the shape of the ellipsoids was determined to a great extent by the rolling over and over of these units and the pressure under which they existed at this time as well as their cooling and consequent contraction, with possibly, as an additional and less important factor, the pressure to which they were subjected subsequent to their complete cooling. In a recent article Gregory describes the ellipsoidal structure in Maine andesites, and writes of the brecciated rock (glassy and stony) which fills the interstices between the ellipsoids.[c] This is confirmatory of my statement that the matrix between the ellipsoids in the Lake Superior region was originally a breccia, in part at least, which is now, however, as the result of pressure, almost always distinctly schistose. The conclusion as to this original brecciated character of the matrix was reached chiefly as the result of microscopic study of thin sections of the schistose matrix.[d] A clastic matrix has been observed filling the interstices of rocks with similar ellipsoidal structure and is found described in the work of Geikie on the

---

[a] The advantage of using the term "ellipsoidal," applied to designate the peculiar parting found in some of the basic igneous rocks, was emphasized in the description of the Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey Vol. XXXVI, 1899, pp. 112–124. The writer has observed, in conversation with various geologists, that in practically every case in which the term "spheroidal" was applied to this parting, the person using it had the idea that it corresponded very closely to the secondary spheroidal parting which is so well known in all igneous rocks. Very naturally confusion is thus caused in the minds of the geologists by the use of the term spheroidal to designate the original parting in the rocks on the one hand, and the structure produced as the result of weathering processes on the other. It seems to me, therefore, more than ever necessary to confine the term ellipsoidal to this original parting and the term spheroidal to the structure produced by weathering.

[b] Mon. U. S. Geol. Survey Vol. XXXVI, 1899, pp. 112–124.

[c] Am. Jour. Sci., 4th series, Vol. VIII, 1899, p. 367.

[d] Loc. cit.

ancient volcanics of Great Britain.[a] In some of the cases mentioned by him, however, this clastic matrix is clearly of sedimentary origin, as lines of sedimentation, with separation into the finer and coarser grained material, are clearly recognized. In none of the numerous cases studied in the Lake Superior region is there any indication that this clastic material is of sedimentary origin, hence it has been concluded that it was due to brecciation. The reservation must be made, however, that some of it may well be a tuff deposit in which, as the result of the small amount that can be studied, no differentiation in grain, etc., is shown.

The mode of formation of these ellipsoids, as suggested, and the presence in them of great quantities of amygdules, seem to point conclusively to the fact that the lava in which they occur is a surface flow, although the flows may have been of submarine formation.

Ellipsoidal basalts identical in every way with those from Michigan, whose characters have been already described, occur in the Vermilion district of Minnesota, and are very widespread. An occurrence at one locality was described several years ago by Winchell.[b] More recently, in the last volume of the Minnesota report,[c] a number of other localities in the Vermilion district have been enumerated, in which rocks having this structure occur. The greenstones possessing this structure have, however, a much wider distribution in the Vermilion district than would be inferred from the description given by the State geologist. Corresponding to their wide distribution in the Vermilion district proper they have also been found by reconnaissance to cover large areas in the adjacent portion of Canada forming the continuation of this district. This distribution is practically the same as that of the Ely greenstones, for this structure can be seen in more or less perfect development on nearly all of the large exposures of that rock. The accompanying illustration (Pl. IV, *A*) shows nothing essentially different from the sketches reproduced in Monograph XXXVI, but is taken from a photograph and is, therefore, of much greater value. The photograph represents an exposure about 50 paces south of the county road 1 mile east of Soudan, just northeast of Jasper Peak.

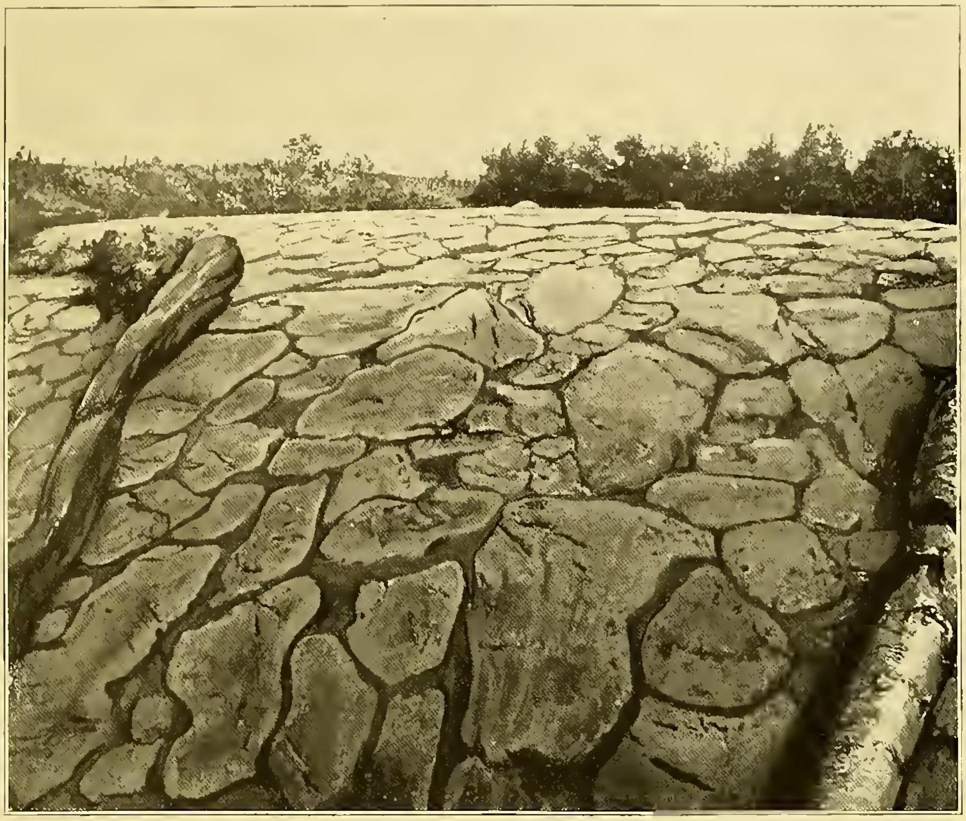
The various observations recorded in Monograph XXXVI concerning

[a] Ancient Volcanics of Great Britain, by Sir Archibald Geikie, Vol. I, 1898, pp. 184 and 193.
[b] The Kawishiwin agglomerate at Ely, Minnesota: Am. Geologist, Vol. IX, 1892, pp. 359-368.
[c] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, pp. 255-267, 274, 276.

the peripheral and concentric arrangement of the amygdules in the ellipsoids were confirmed by repeated observations on similar occurrences in the Vermilion district. At one place on the hill just west of Ely and not very far from the last house in the town, it was noticed that the amygdules were concentric on one side of the ellipsoids, although a few were scattered through the ellipsoids. In this case the exposure showed a transition from amygdaloidal ellipsoidal rock to amygdaloidal nonellipsoidal basalt, both of essentially the same grain. The exposure is about 20 paces in width north and south. It looks very much as though the ellipsoidal portion of this ancient lava represents the surface of the flow, which was more viscous than the inner portion and consequently more readily broken. This being true, such a relationship readily explains the occurrence of a transition from ellipsoidal to nonellipsoidal forms of the same rock, as discussed in detail in Monograph XXXVI, to which reference has repeatedly been made. Such gradations in these ancient lavas are shown by a number of observations taken at different places. One passes in the field from a fine-grained amygdaloidal ellipsoidal basalt to an ellipsoidal basalt in which, by gradual transition, the grain has become considerably coarser; it is then an ellipsoidal anamesite, if we use the terms basalt, anamesite, and dolerite to express the degrees of coarseness of crystallization; it then grades into a coarse-grained ellipsoidal dolerite, which in its turn grades into an even coarser dolerite without marked ellipsoidal parting. Continuing, this same sequence is gone over in reverse order, from the coarse, massive dolerite to the fine-grained ellipsoidal basalt. The best place to get this complete sequence is on the bare hills south of Moose Lake, along the section line between secs. 32 and 33, T. 64 N., R. 9 W. Another place in which the transition from the fine amygdaloidal ellipsoidal basalt to the massive dolerite can be excellently seen is north of Long Lake. It is about 500 paces, or one-fourth mile, north of the southeast corner of sec. 9, T. 63 N., R. 12 W.

Observations show that the amygdules are not the only features which are common in the ellipsoids, as the ellipsoids are also commonly spherulitic.[a] In fact, the spherulites have been observed only on exposures which show a more or less perfect ellipsoidal parting. The best spherulites have been seen where the ellipsoids are typically developed and show the following

[a] Cole and Gregory, Quarterly Jour. Geol. Soc., Vol. XLVI, 1890, p. 311.



A. ELLIPSOIDAL PARTING IN GREENSTONE.

B. ELLIPSOIDALLY PARTED GREENSTONE, SHOWING SPHERULITIC DEVELOPMENT.

relations to these ellipsoids. The smallest spherulites occupy the extreme outside of the ellipsoids. From the outside they increase in size toward the center, where, if the rock is there spherulitic at all, the largest spherulites are developed. Sometimes the development of the magma into a spherulitic rock did not reach entirely to the center, which is then developed as a massive dolerite of normal character. It is very noticeable that while the spherulites occur in the very fine-grained lavas they are apparently equally common in some of the more coarsely crystalized forms when these phases are ellipsoidal. The spherulitic and amygdaloidal structures sometimes occur together, but most commonly they are not developed in the same rock. Apparently the presence of one does not altogether preclude the existence of the other, although it amounts very nearly to this. Thus, in passing over the particular section through the ellipsoidal amygdaloidal lavas, which was noted above as occurring north of Long Lake, we find that the amygdaloidal ellipsoidal fine-grained lava is first nonspherulitic. Soon, however, the spherulites begin to appear and gradually increase in importance, the amygdules decreasing correspondingly in quantity and the grain of the matrix between the spherulites increasing also in size. The spherulites, however, are wanting in the coarsest non-ellipsoidal phases of the lava. The arrangement of the spherulites in concentric circles made up of spherulites of larger and larger size as the center is approached shows, as does the concentric arrangement of amygdules in the ellipsoids, that each ellipsoid must be reckoned with as a unit. Observations show that small spherulites occur on the outside of a spherulitic mass, where crystallization continues for only a short time, while the larger spherulites, requiring proportionally a longer period for their formation, occur deeper down in the rock.

Magnificent exposures of these spherulitic ellipsoidal greenstones occur on the hills north of Long Lake for the greater portion of the distance between this lake and Bass Lake, in secs. 9 and 10, T. 63 N., R. 12 W. One of the finest exposures seen was that occurring on the high hill about 500 paces south of the meander corner on the shore of Bass Lake. The illustration presented in *B* of Pl. IV is made from a photograph of this exposure and shows the spherulitic character of the ellipsoids; the eight spots in the photograph are the spherulites. The somewhat schistose, brecciated matrix between the ellipsoids can also be seen in the illustration.

Other good exposures of spherulitic, ellipsoidal greenstones, in which four or five rows of spherulites can be seen, occur in the northeast corner of sec. 7, T. 63 N., R. 11 W. Perhaps even better ones can be seen south and southeast of Jasper Lake, especially in sec. 6, T. 63 N., R. 9 W. Here the hills are nearly bare and exposures extend almost continuously from the south shore of Jasper Lake eastward along the section line to the south quarter post of sec. 6, T. 63 N., R. 11 W.

These ellipsoidal or aa greenstones have been subjected to orogenic movement, and when in the zone of fracture[a] they have been jointed, and in places brecciation has also taken place. A different result followed when the rocks were more deeply buried and subjected to great pressure, which produced interesting structures that are in some places now exposed at the surface. The ellipsoids then, instead of being fractured, were mashed into disks, just as one could mash a lump of stiff dough into a disk-shaped body. The cross section of such a mashed ellipsoidal greenstone shows that the ellipsoids have enormously elongated axes, approximately parallel to the direction of minimum pressure, and a proportionally short one in the direction of greatest pressure. Various stages of this deformation have been observed. In extreme cases these rocks have a banded appearance, the material of the ellipsoids forming bands of dense material alternating with other bands which consist of what was the matrix between the ellipsoids. This rapid alternation of bands of differing material—the bands derived from the matrix may be an inch and a half in thickness, the bands from the ellipsoids being usually a little thicker—very closely simulates true bedding, and might very readily be construed as such on a hasty examination. Especially might it be so taken in cases where, as frequently happens, the exposures are only a few square feet or at most a few square yards in area. If one had large areas of these massive ellipsoids to study, however, the bands, if examined in detail, would be found to be relatively short and to be made up of enormously elongated lenses. Such large exposures are, however, rare. One of the best exposures of rock of this sort is on the high ridge south of the exploring camp on the south side of Moose Lake. The rock here is the typical spherulitic ellipsoidal greenstone, and shows very nearly clean exposures over an

[a] Principles of pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Pt. I, 1896, p. 696.

area several hundred paces long. In the center of this large exposure the ellipsoids are relatively little mashed, and show the spherulitic structure within them as well as the matrix between them. This was evidently a part of the rock mass that acted as a buttress, and was not affected by the mashing, as was the rock on each side of it. On the sides of the ridge the ellipsoids are much flattened. The rock in places passes into a greenstone-schist in which the ellipsoidal structure is totally obliterated. Between these green schists on the one hand and the typical ellipsoidal greenstone on the other there are various gradations. The intermediate phases show a certain coarse banding which, by a careless observer, might be mistaken for lines of sedimentation. This banding is produced in the way indicated above, the bands being of two kinds, one kind produced from the matrix and the other produced from the original ellipsoids.

Still another excellent example of this pseudobedded structure may be seen in the Archean just north of the railroad near the east end of the place where the Duluth, Port Arthur and Western Railroad first reaches the shore of Gunflint Lake from the east. This is north of the railroad track and distant from it from 75 to 150 paces. To the north the greenstone is fairly massive, and in places is distinctly ellipsoidal. Toward the south, nearer the overlying sedimentaries and consequently nearest the plane along which movement must have taken place during the folding of the rocks, it becomes decidedly schistose. The ellipsoidal masses are flattened to such an extent as to give a rough banding to the rock.

This description of the ellipsoidal structure in these greenstones would not be complete if attention were not called to the frequency of its occurrence in the various districts of the Lake Superior region. Thus, for example, it has been described from the Marquette and the Crystal Falls districts of Michigan, and one can state with a fair degree of assurance, from the occurrence of large quantities of greenstones in the Penokee-Gogebic of Michigan and Wisconsin, that it also occurs there, although it has not been described from that district. It has also been observed by the writer in a number of places in the Menominee district of Michigan and in the Mesabi district of Minnesota. Lawson describes it in the rocks of the Lake of the Woods region.[a] The same structure has been described

[a] Geology of the Lake of the Woods region, by A. C. Lawson: Geol. and Nat. Hist. Survey of Canada, 1885, pp. 51-53cc.

from the Michipicoten iron-bearing district on the east side of Lake Superior by A. B. Willmott,[a] and Dr. S. Weidman, of the Wisconsin Geological and Natural History Survey, states that it occurs in greenstones of supposed Huronian age in the vicinity of Wausau, Wis. It has been observed in the Archean greenstones on Lake Nipigon in Ontario, Canada. As the result of field studies of the Keweenawan volcanics of the north shore of Lake Superior in 1900, the writer knows that it occurs also in them. Although so very common throughout the Lake Superior region in the rocks of pre-Cambrian age, it appears to be relatively rare in the petrographically similar rocks of later age found elsewhere in North America. This structure has been found to be so common throughout the Lake Superior region that it is now considered characteristic of the pre-Cambrian greenstones of the region. It is not, however, confined to any one of the divisions of the pre-Cambrian rocks. The rocks in which it occurs range from the Archean of the Vermilion district of Minnesota and the adjacent Canadian districts and the Marquette district of Michigan, to the Keweenawan. It occurs within the greatest surficial areas of the Archean. This same structure has been found by Geikie in the lavas of Great Britain.[b] In a letter to the writer Geikie says: "This remarkable structure appears to be far more common in lavas of all ages than I supposed. It is admirably developed in our Arenig lavas, and I have lately found it in those of the Old Red sandstones and Carboniferous system."

MICROSCOPIC CHARACTERS.

The rocks composing the Ely greenstone have been divided according to their macroscopic characters into the porphyritic and non-porphyritic varieties, the normal diabasic or ophitic textured forms, the amygdaloidal, spherulitic, and ellipsoidal forms. Stress has been laid upon some of the principal macroscopic characters, and these divisions have been made merely for the purpose of aiding in the study of the rocks and not because the varieties were distinguished by important differences in microscopic characters, except in a few cases. As the reader would infer from their age and from the use of the name greenstone in connection with them, these

---

[a] The Michipicoten Huronian area, by A. B. Willmott: Am. Geologist, Vol. XXVIII, 1901, p. 14. The nomenclature of the Lake Superior formations, by A. B. Wilmott: Jour. Geol., Vol. X, 1902, p. 71.

[b] Ancient Volcanics of Great Britain, by Sir Archibald Geikie, Vol I, 1898, pp. 184 and 193.

rocks are very much altered. The original minerals that remain are very few. The microscope discloses the following original constituents: Hornblende, augite, feldspar, quartz, titaniferous magnetite, and apatite. The original hornblende is the common brown variety. The augite varies from yellow to yellowish green and possesses its normal characters. The feldspar usually shows broad twinning lamellæ, although in some cases it was found in imperfect sheaves. In one case it was distinctly seen to have been formed prior to the titaniferous magnetite, as the magnetite, occurring in large plates, incloses lath-shaped feldspars. The feldspar is generally very much decomposed, so much so that one can not determine its exact characters. It is presumed to be a labradorite. There is very little quartz, but some was found occurring in micropegmatitic intergrowth with the feldspar, and is presumed to be a primary constituent. Sometimes it fills irregular interstices between the other minerals as primary quartz representing the last product of the crystallization of the rock. Magnetite and apatite show nothing uncommon.

The secondary constituents are common green hornblende, actinolite, biotite, chlorite, sericite, epidote, zoisite, sphene, rutile, feldspar, quartz, pyrite, and hematite. The feldspar has usually altered to a mass of sericite, kaolin (?), feldspar, and quartz. In some cases it is completely saussuritized. There were observed occasional irregular but in general rounded serpentinous areas, which are strongly suggestive of aggregates of olivine individuals in which the olivine possesses no definite crystallographic outline.

TEXTURE.

The great majority of the greenstones are massive rocks, varying from fine to coarse in grain. The textures they originally possessed have to a certain extent been obscured by the various processes of alteration to which they have been subjected. Both fine- and coarse-grained greenstones and all of the intermediate phases show locally porphyritic texture, the phenocrysts being usually of feldspar, but occasionally of brown hornblende. In the coarse-grained rocks the ophitic texture predominates; in the even-textured, fine-grained rocks the following are commonly developed: Ophitic, microophitic, intersertal, pilotaxitic, hyalopilitic, flowage, and spherulitic textures. The ophitic and microophitic textures are the most common, and the mineralogic composition is generally that so characteristic of the metadolerites (diabase) and metabasalts. The rocks possessing these textures occur in very large quantity throughout the district. These textures are common in the recent basalts. The mineralogic composition of the rocks is also the same as would be produced in recent basalts by alteration. Hence, in the absence of chemical analyses, the writer feels warranted in asserting that the greater portion of these greenstones was derived from the alteration of originally basaltic rocks.

Spherulitic texture is fairly common in these altered basalts, and on account of its somewhat greater interest deserves a little more detailed consideration than has been given to the others. The spherulite occasionally has at its center a very small crystal of plagioclase surrounded by fine sheaves of feldspar, and these spherulites are very similar to those described some years ago from Michigan.[a] The feldspars are brownish when seen under low power and grayish when examined by high power, as the result of the innumerable minute crystals of epidote, a few hornblende individuals, and reddish-brown to black spots of ferruginous material. Other spherulites consist largely of feldspar, but between the feldspars occur needles of actinolite, which seem to have been derived from some original ferromagnesian mineral which, with the feldspars, formed the spherulite. There were found in one case in a much altered greenstone, instead of the usual feldspar spherulites, radial masses of rich green chlorite with silky luster. The microscope showed a few crystals of magnetite and some epidote in these spherulites in addition to the chlorite.

With the above kinds of rocks, which are unquestionably of basaltic character, there are rocks that possess an intersertal, pilotaxitic, and hyalopilitic texture, in some of which porphyritic feldspars, occurring in isolated individuals or in groups, are very common. In these rocks there seems to be a large proportion of brown hornblende, sometimes occurring as phenocrysts. The general appearance of the rocks is like that of the andesites. It appears that, associated with the basalts and playing a subordinate rôle in this district, there are rocks of intermediate composition which were originally andesites—both hornblende- and pyroxene-andesites—and that we are justified in stating that meta-andesites form a part of the Ely greenstone.

---

[a] The Crystal Falls iron-bearing district of Michigan, by J. Morgan Clements: Mon. U. S. Geol. Survey Vol. XXXVI, 1899, p. 111.

SCHISTOSE GREENSTONES.

The various greenstones thus far described have been very much changed by chemical action, as is shown by the number of secondary minerals which now replace the original ones. In many cases dynamic action subsequent to or accompanied by the above changes has produced schistose forms of these greenstones. These schistose greenstones are not nearly so common, however, in the Vermilion district as one would be led to suppose from a perusal of the literature which has been published on this district. In this literature these rocks have frequently been spoken of as greenstone-schists. This term seems to the writer to convey a wrong idea of the character of the rocks as a whole, though it is fitting in certain cases. The greenstone-schists or green schists are in reality a very subordinate phase of the Ely greenstone, and in the great majority of cases are of purely local occurrence and very subordinate extent. They have been formed along zones of excessive deformation and grade into massive granular rocks. For this reason the term schistose greenstone has been preferred to indicate them. In these schistose rocks all of the original minerals have been changed by metasomatic action, and as a result of movement in the rocks produced by shearing stresses, the original textures have also been almost completely obliterated.

GENERAL CHARACTERS.

These rocks are schistose in character and appear in various shades of green. Only one macroscopic structure has been observed which would lead to the determination of the original characters of the rocks. An imperfect, nearly obliterated, amygdaloidal structure was observed in one case. A microscopic study of the rocks shows that the constituents are small and the rocks very dense in texture. The various minerals to be enumerated generally have their long directions approximately parallel, this arrangement producing a schistose structure. In some cases almost complete recrystallization seems to have taken place, and in these cases larger individuals have been produced. Occasionally the hornblende and chlorite appear in large porphyritic individuals inclosing other constituents of the rock. Constituents of these rocks are biotite, muscovite, chlorite, sericite, calcite, epidote, zoisite, pyrite, and limonite. In some cases the secondarily produced hornblende has undergone a tertiary change and has been chloritized.

The above rocks, when examined in the laboratory, give no clue to the character of the rocks from which they were derived, if we except the case of the specimen containing the amygdules. Classified according to their mineralogic composition we would call them chlorite-, amphibole-, and biotite-schists, and gneisses. When studied in the field, however, their intimate relations with the greenstones and the gradations observed between the schists and the massive greenstones prove conclusively that they have been derived from rocks similar to those from which the massive greenstones that now predominate throughout the district have been derived—in other words, from dolerites, basalts, and andesites.

ORIGIN OF ELY GREENSTONE.

There can certainly be no reasonable doubt in the mind of the reader as to the original character of the rocks described as constituting the Ely greenstone of the Vermilion district of Minnesota. The various textures and structures that the rocks possess are such as are present only in igneous rocks. However, even though it may be conceded that the greenstone formation is of igneous origin, there remain still the further queries: Are the rocks constituting it intrusive or effusive in their character, or are rocks of both of these modes of formation present in the complex? Furthermore, if both occur, which mode of origin is the predominant one? These points may well be discussed here. To the first query the answer must be given that the observations recorded show that both kinds of rocks—both effusive and intrusive—are present. The answer to the second query, as to which of these predominates, can be given only with some doubt, as it is very difficult to make a quantitative estimate of the areal distribution of rocks that are so similar in character. From personal observations, however, the writer has been impressed by the very wide distribution of the greenstones that possess characters indicative of effusion. This has led him to place the greenstones with the surface flows; but the reader must be cautioned to include under the term surface flows those which may have been poured out under water—submarine flows—and which were thus, perhaps, under relatively high pressure, as well as those that reached the surface of the land. In either case the mode of origin outlined for many of these greenstones postulates a surface upon which they could rest. Hence, if interpreted in the strictest sense, they do not actually represent the original crust of the earth, as Winchell considers them to do.[a] Nor, showing volcanic characters as they do, can they be considered as a part of the earth's crust produced by downward crystallization. They must be, indeed, somewhat younger than the original crust. Nevertheless, since the greenstones are the basement upon which rests a great series of sediments that can be correlated with sediments in other areas which have been regarded as of Lower Algonkian age, we have classed the igneous greenstone basement in the Vermilion district as of Archean age.

The intrusives that are considered to form a part of this complex are those which are of essentially the same nature as the volcanics, but which differ slightly in their mode of occurrence. They are those portions of the magma that penetrated the contemporaneous flows as dikes, and in some cases, perhaps, are the material filling the conduits which connected some of the flows with the magma mass from which they came. In one instance a fragment of a greenstone was found included in a somewhat different greenstone. The fragment was identified as being similar to, and presumably derived from, one of the greenstones of the complex. The intrusives included in the Archean greenstone complex belong to the same period of formation as the lava flows with which they are associated. These intrusive rocks are of essentially the same mineralogic and chemical composition as the volcanics themselves.

It remains to be stated that we recognize the possibility, and, indeed, the great probability, that there have been included in the areas mapped as underlain by this Archean complex an occasional intrusive rock considerably younger than the Ely greenstone proper. These greenstones are cut by a number of dikes of relatively recent age and yet of essentially the same character as the greenstones, except that they are less metamorphosed. No doubt many others were unrecognized, and, indeed, were altogether unseen on account of poor exposures.

CONTACT METAMORPHISM OF ELY GREENSTONE.

CONTACT EFFECT OF GRANITE ON THE ELY GREENSTONE.

In the preceding pages general statements have been made concerning changes which the greenstones have undergone since they were formed In addition to those mentioned, which were essentially changes brought about as the result of ordinary mountain-making forces and of percolating

[a] The origin of the Archean greenstones of Minnesota: Geol. and Nat. Hist. Survey of Minnesota, Twenty-third Ann. Rept., 1895, pp. 4–24.

waters, other changes of a far-reaching character have taken place in them. In all of the instances which will be cited the chief agent of metamorphism appears to have been the contact action of certain intrusive acid rocks. It is not for a moment to be supposed, however, that the metamorphism of the rocks should be ascribed solely to the action of these intrusives; yet this is the most obvious cause, and probably the final controlling cause.

In the course of the field work on the Vermilion district, it was noticed, when the exposures of greenstone possessing the general characters already outlined for that rock were studied, that a great number of them were cut by dikes of acid rock, and that these dikes were of varying size. It was further observed that near the central portion of the district these dikes were relatively few, but that as the southern and northern limits were approached they gradually increased in number until the greenstones were in places literally permeated by dikes of acid rock. On continuing farther from the central part of the district the main body of the granite was in every case finally reached. When this body was reached, however, it was found to contain occasional masses of Archean rocks of varying size, which were practically surrounded by and thus included in the granite. The relations are clearly those of intrusion, a younger acid rock being intruded into and including fragments from the older Ely greenstone. In brief, the relations are the same as those which exist between the batholiths of granite and the contiguous greenstones of Rainy Lake[a] and Lake of the Woods, and which have been so clearly described by Lawson. It was further noted that this intrusion was accompanied by a marked change in the character of the Archean complex. Where the granite dikes are few, the characters of the greenstone formation remain essentially unchanged. When the dikes have become numerous, however, the greenstones are altered to amphibolitic and to a less extent to micaceous rocks, usually of somewhat darker color than the normal greenstones. The main macroscopic characters are practically unchanged. Thus, for example, in these amphibolitic rocks one can still recognize the characteristic ellipsoidal and amygdaloidal structure of the greenstones. A splendid exposure of these hornblendic rocks can be seen in the southeast quarter of sec. 3, and the northeast quarter of sec. 10, T. 61 N., R. 14 W. These rocks, while

[a] Report on the geology of the Rainy Lake region: Geol. Nat. Hist. Survey Canada, 1889, F.

possessing on the whole a massive structure, nevertheless have, as it were, an incipient fissility, or cleavage, which has been produced by the process of recrystallization through which they have gone, as the result of which there has been a production of amphibole needles and chlorite flakes, and also a general tendency toward a parallel arrangement of the needles and flakes. The secondary feldspar has also been affected in its crystallization, and aids in emphasizing the parallel structure. This parallelism has developed a fissility which is not sufficiently marked to warrant their designation as schists. They merely split more readily in one direction than in another.

When the contact between the main granite masses and the Archean greenstone is approached, the Archean rocks are usually found to have lost all of their characteristic features and to have been recrystallized into amphibolitic schists and gneisses which very rarely retain any recognizable greenstone character. The gradation is, however, so gradual and the steps can be followed so clearly in the field that after a field inspection no doubt as to the correctness of the above conclusions can remain in the mind of any close and impartial observer.

MINERALOGIC COMPOSITION OF THE METAMORPHOSED ROCKS.

These amphibole-schists and mica-schists, derived from the greenstones, consist of the following constituents in varying proportions: Common green hornblende, actinolite, biotite, muscovite, chlorite, epidote, calcite, sphene, quartz, feldspar, pyrite, and magnetite. The mica is present in very small quantity and is always associated with amphibole. It is only occasionally that the mica occurs in such quantity that the rock can be referred to as a mica-schist. Banding is very commonly present, as the concentration of some of the darker minerals was greater in certain portions than in the areas immediately adjacent.

The origin of these metamorphosed greenstones, now schistose amphibolitic rocks, is such as would be expected from their distribution and from their relationship to the granites. They always lie between the normal greenstones and the granites, occupying a belt of varying width, which it is impossible in the field to delimit sharply. This zone of schists has therefore been only approximately indicated on the maps.

The presence of these amphibolitic schists adjacent to the granite has been noticed by nearly every observer who has been in this district. On a manuscript map by Irving this belt of schists is outlined. Special attention has been called to them by both A. and N. H. Winchell in their published reports. The earliest explanation offered was that of A. Winchell,[a] who studied the good exposures of these schists upon Burntside Lake and there found them, as has been described, permeated by the granite. Figs. 1 and 2, from his report, illustrate the occurrence. His conclusion was that they were derived from graywackes by metamorphism.[b]

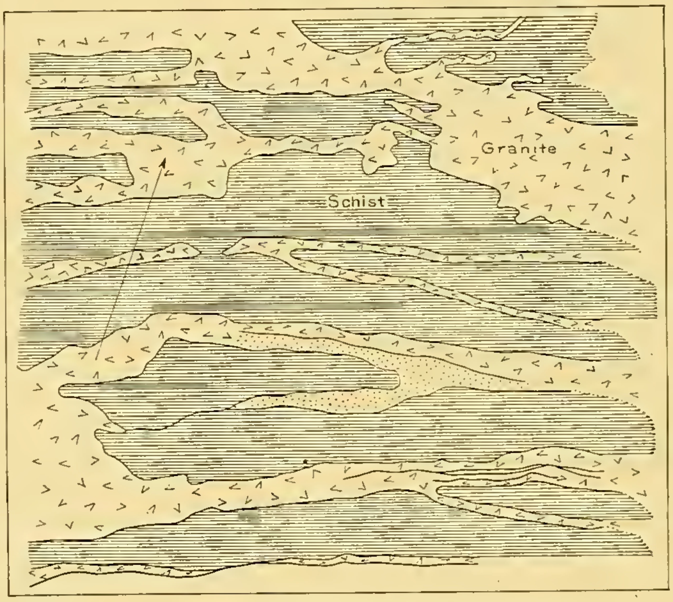


Fig. 1.—Reproduction of sketch by A. Winchell, showing the intricate relationship between the granite of Burntside Lake and the amphibole-schists.

N. H. Winchell[c] refers to this belt of schists, and concludes that they have been "produced by the granitic intrusions or by the force which accompanied them," and that when acid clastic rocks were affected the mica-schists were produced, and when the basic greenstone was involved the amphibole-schists were produced. To these rocks Winchell applied the name Coutchiching, using it in the sense proposed by Lawson.[d] In his

[a] Geol. and Nat. Hist. Survey of Minnesota, Fifteenth Ann. Rept., 1887, pp. 40–41.

[b] Geol. and Nat. Hist. Survey of Minnesota, Fifteenth Ann. Rept., 1887, pp. 172–178. Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 246.

[c] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, pp. 272, 273, and 283.

[d] Report on the geology of the Rainy Lake region: Geol. and Nat. Hist. Survey of Canada, 1889, F. pp. 21–35 et seq. Geology of the Rainy Lake region: Am. Jour. Sci., 3d series, Vol. XXXIII, 1887, p. 477.

general statement in the preface of the final volume of the Minnesota survey, Winchell abandoned the use of the term Coutchiching, for his studies showed that he could not in this district include any definite series there-

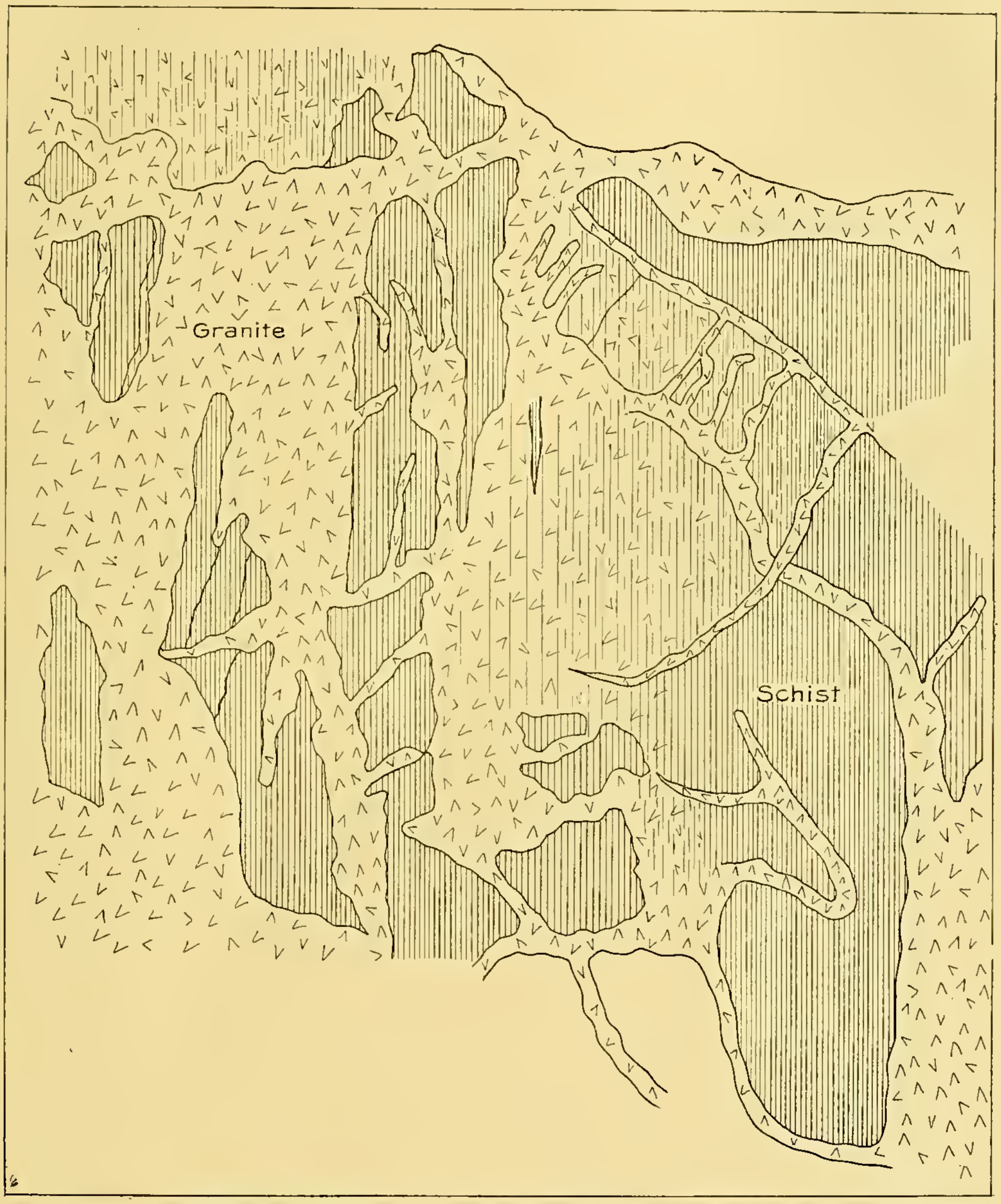


Fig. 2.—Reproduction of sketch by A. Winchell, showing the intricate relationship between the granite of Burntside Lake and the amphibole-schists.

under[a]. The rocks that were first included under this term can be shown to be to a large extent formed by metamorphism from the Ely greenstones as above described. The remaining portion has been formed by metamorphism of sediments of Lower Huronian age, as described in Chapter IV. Should Lawson's name Coutchiching be applied to the amphibole- and mica-schists lying between the granites of the district and the rocks that have been intruded by the granite, we should have included under this term two series of rocks which, though possessing the same schistose characters, are demonstrably of different age, both as regards their initial period of formation and their period of metamorphism. The use of the name Coutchiching is not warranted in connection with the rocks of the Vermilion district of Minnesota, and Lawson's insistence[b] on the presence of a series of rocks in this district comparable to his supposed Coutchiching series is explainable only as due to his unfamiliarity with the district.

The character of the metamorphism involved in the change of the greenstone of the Archean from a massive rock to a predominantly schistose rock of a different mineralogic character might be made a matter of question by some who wish to classify metamorphic rocks into those produced by contact action and those produced by regional metamorphism. The agents, however, in both cases are the same. They are heat, pressure, and water, and whether these agents owe their activity to the intrusion of an igneous mass of rock or to orogenic movement is merely a matter of detail. In the present instance the field relations of the greenstones to the metamorphic rocks and the granite show that the metamorphism of the greenstones accompanied the intrusion of the granite. Hence, as this was the prime agent in their production, they have been classed under contact metamorphic products. Yet while these schistose rocks may well have been produced by the intrusion of igneous masses that caused recrystallization of their already partially altered original minerals, nevertheless essentially the same chemical constituents are present in them now as were present in them formerly. The rocks have merely been recrystallized under pressure.

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, pp. 14 and 15.

[b] Geol. and Nat. Hist. Survey of Minnesota, by N. H. Winchell; Final Rept., Vol. IV. Review by A. C. Lawson, Am. Jour. Sci., 4th series, Vol. IX, 1900, p. 151.

This has resulted in the formation of minerals with higher specific gravity[a]—hence such as occupy less space—and produced an arrangement of these minerals which makes them conform to the law of the production of secondary minerals in schists, as explained by Leith.[b] Moreover, the great additional space within this portion of the earth's crust which was required by the intrusion of the granite has been partly supplied by this very change of the preexisting greenstones into related rocks that occupy less volume. In their formation, pressure has, of course, been a very important factor; hence the more frequent occurrence among them of schistose forms of rocks.

CONTACT EFFECT OF GABBRO ON ELY GREENSTONE.

In three areas the Archean Ely greenstone lies in juxtaposition with gabbro of Keweenawan age. A contact of the greenstone with the gabbro occurs east of Disappointment Lake, in secs. 26 and 35, T. 64 N., R. 8 W. Here the anticline of Ely greenstone has been cut across on its east side by the gabbro. Another contact occurs in secs. 1 and 2, T. 64 N., R. 6 W., at the southwest side of Gobbemichigamma Lake. From sec. 25, T. 65 N., R. 5 W., eastward through secs. 30, 29, 28, and 27, T. 65 N., R. 4 W., we find an Archean anticline which is not in contact with the gabbro, being separated from it by a minimum distance of perhaps 200 paces and a maximum distance of half a mile. The greenstone has been metamorphosed by the gabbro, although it has not been affected nearly so extensively as it is where it is in contact with the granite. Macroscopically no great difference can be observed between the metamorphosed and the unmetamorphosed greenstones. They are in all cases massive rocks, and the metamorphosed portions appear to have essentially the same characters as the remaining unmetamorphosed portions, although the former weather somewhat more readily than the latter and have a rusty-brown color.

The effect of the gabbro on the greenstone in producing metamorphosed rocks can be best seen in exposures on the west side of Gobbemichigamma Lake in the sections above mentioned, on

[a] Metamorphism of rocks and rock flowage, by C. R. Van Hise: Bull. Geol. Soc. Am., Vol. IX, 1897, p. 291.

[b] Manuscript.

the south flank of the Twin Peaks ridge. Here the texture of the greenstone is characteristically ophitic, a secondary hornblende taking the place of the original pyroxene. When metamorphosed by the gabbro we find the ophitic texture perfectly preserved with, however, a large quantity of biotite as a secondary product. This biotite has accumulated around the edges of the hornblende between the hornblende and the feldspar, and is especially concentrated along evident shearing planes where normally—that is, in the greenstone unaffected by the gabbro—one would find a large amount of chlorite derived from the hornblende. With rocks like the above there is associated another, showing the ophitic texture poorly preserved and with brownish-green, massive hornblende constituting most of the rock, and with hypersthene occurring in more or less porphyritic areas. This hypersthene is very fresh and seems to be a product of the action of the gabbro on the greenstone. In other cases ophitic textured greenstones seem to contain a very much larger amount of a brownish-green hornblende and magnetite than these greenstones normally contain, and in this instance the large quantity of magnetite, and possibly also the brown hornblende, is assumed to be due to the action of the gabbro. In general, there are produced from the greenstone, by metamorphism of the gabbro, rocks which contain a large percentage of biotite and varying quantities of hypersthene and magnetite. As a result of their mineralogic character such rocks have a rusty-brown color, and the texture, although distinctly ophitic, is inclined to become granular as the new minerals increase in quantity. These rocks disintegrate much more readily than do the greenstones.

RELATION OF ELY GREENSTONE TO ADJACENT FORMATIONS.

The relations of the greenstone complex to the adjacent formations have already been briefly stated, but will be recapitulated. Wherever the greenstone complex is in contact with any sediments all the larger masses lie above and are infolded in it. When these sedimentaries are normal clastic deposits they lie above and contain numerous fragments of the greenstones, showing that the greenstone complex is the older formation. When the greenstones lie next to other igneous rocks they are found to be penetrated by them. Hence all of the relations of the greenstone complex to the various adjacent formations prove its greater age. A detailed description of some of the contacts of the various formations of the district with the greenstones, in which their relations to one another will be given, will be found under the discussion of these formations.

ECONOMIC VALUE OF THE ELY GREENSTONE.

The Ely greenstone rocks of the Vermilion district are suitable for building stones, especially for foundations, for which the unworked stones can be used. They are very tough, and there is hardly sufficient demand for stonework to warrant their being cut and used for the superstructure of buildings, even if their color were suitable. Their color is, however, uniformly so dark that they would rarely be used for other portions of buildings than foundations and trimmings. This stone is eminently adapted for use as road material, as there is an inexhaustible supply, and it is generally so distributed that it can be obtained for use on existing roads at small cost.

Occasionally the discovery of bodies of magnetite ore in the greenstones is announced. The greenstone contains large quantities of magnetite as an essential constituent. This occurs, however, disseminated through the rock in very small particles, which make up an exceedingly small percentage of the total mass. While the occurrence of the ore bodies reported has in no case been verified, it would not be at all surprising should iron-oxide bodies, of very limited extent, however, really be found. The explanation of their occurrence would be similar to that of the occurrence of almost identical iron-oxide masses in the gabbro; that is, they are the result of processes of segregation from the basic magma. It is not believed, however, that any such bodies that may be found would prove to be of commercial value. The iron oxide occurring in minute quantities scattered through the greenstone contains titanium—it is a titaniferous magnetite—and the probability is that any ore bodies found in this greenstone would likewise consist of titaniferous magnetite. They would then correspond in their chemical composition, as well as in their mode of origin, to the ore bodies in the gabbro. Moreover, since the processes of liquation and fractional crystallization, as the result of which such bodies are formed, would be most fully carried out in those cases where the rocks remain under essentially the same conditions of temperature and pressure for a great length of time, we should naturally expect to find the largest bodies of oxide in the coarsest-grained rocks. Hence, continuing the comparison of the bodies of ore which one would be likely to find in the Archean greenstones with those in the adjacent Keweenawan gabbro, we see that they would probably be very much smaller than those in the gabbro, since the greenstones with which they would occur are of much finer grain than the gabbro. Moreover, as the size of the mass of magma has an important bearing upon the rate of cooling, we may say that the larger the mass of magma the larger the ore body. For this reason also we should expect to find smaller bodies of oxides in the greenstone than in the gabbro.

In many portions of the world very important ore bodies containing other metals than iron are found associated with rocks of essentially the same composition as those forming the greenstone complex. The question may well be asked, What are the chances of finding silver, nickel, and cobalt ores, to mention some of the most important, in association with these greenstones? I would answer that there is practically no chance. In other regions the ores mentioned occur as contact deposits which owe their occurrence to the intrusion of rocks allied to these greenstones into younger rocks, the deposits being found in fissures occurring within the younger rock, within the older rock, partially in both, or along the contact between the two. Although these greenstones cover a broad area, yet, since they are themselves the oldest rocks, we can not expect to find such deposits in them in very large quantity unless they occur within the greenstones themselves as the product of processes of segregation—processes which, as has been intimated, may have given origin to certain iron-ore deposits reported to occur in them, but whose existence remains unverified. Winchell refers to the occurrence of a gold-bearing quartz vein in the following words:[a]

> At the west end of Long Lake, SW. ¼ SW. ¼ sec. 30, T. 63 [N., R.] 12 [W.], is a conspicuous display of quartz and granite, the former carrying gold. An average sample selected from the dump, assayed by F. F. Sharpless, gave $8.64. Some casual working has been done on this vein, and numerous assays show, according to the statement of Mr. McIntosh, one of the owners, an average of over $10 per ton. The vein is traceable about an eighth of a mile, a little north of east, with an irregular width reaching a maximum of about 80 feet. It accompanies a granite dike. The ore is not abundant, but is in irregular streaks in the quartz.

Thus far no gold-bearing veins which have paid for the working of them have been found in the Vermilion district.

[a] N. H. Winchell, Geol. and Nat Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 258.

INTERESTING LOCALITIES.

Under this heading there will be found special descriptions of certain localities where the rocks show especially well some of the characters already described, or for other reasons are considered worthy of more detailed mention than has been made of them in preceding pages. These descriptions of localities may not perhaps be read by the general reader, but it is hoped may be useful to future students of the geology of the district who may wish to verify the statements herein made, and who would therefore desire to visit some of these places.

Some of the best places at which the general characters of the Ely greenstone may be studied are on the hills near Ely. These hills are very nearly bare, and numerous exposures of the greenstone may be found on them. The ellipsoidal parting is well shown in exposures in the cut on the south side of the railroad track west of the station, and can be seen in numerous places on the bare hills between Ely and Long Lake. Amygdaloidal structure is also very commonly present. No spherulites were observed here, although these are abundant on the high hills due north of Ely, on the north side of Long Lake. On the hill west of the town and south of the water tank ellipsoidal parting, with peripherally arranged amygdules, may be observed, and at one place not very far from the road leading up to the cemetery the transition from the ellipsoidally parted portion into the nonellipsoidal greenstone can be seen. The greenstones on this hill are cut by dikes of granite-porphyry. Just northeast of the Methodist church on the east side of Ely numerous basic dikes are found cutting the greenstones. About a mile and a half south of Ely is a bare ridge, bordered on the north and south by considerable depressions, on which there are many exposures that show the amygdaloidal and ellipsoidal characters of the greenstones. Irregular lines, which seem to represent flowage lines, run through these rocks in many places. This ridge offers a fairly good place for the study of the volcanic characters of the greenstones. It must be noted, however, that the greenstones in this ridge have been extremely altered and in many places are more or less completely schistose, and would now be spoken of as amphibole-schists. This alteration is due to the intrusion of the Giants Range granite, which is present in these rocks in numerous dikes, and which occurs in mass a short distance to the south. These exposures, therefore, besides offering opportunity for a study of the general characters of the greenstone, are very favorable for a study of the metamorphism of the greenstone into the amphibole-mica-schists, which, as seen in isolated exposures, in many cases offer little evidence of their derivation from the greenstones.

POSSIBLE TUFFS ASSOCIATED WITH THE GREENSTONES.

Reference has already been made to the fact that, associated with the greenstone, we not uncommonly find masses of tuffaceous-looking rocks, which, since they show no characters clearly indicative of sedimentation, have been included with the greenstones as interbedded tuff deposits. Included in this category are deposits occurring at the following places:

North 200 paces, west 1,950 paces from southeast corner sec. 17, T. 62 N., R. 13 W.

North 600 paces, west 1,000 paces from southeast corner sec. 30, T. 63 N., R. 11 W.

North 1,930 paces, west 1,000 paces from southeast corner sec. 3, T. 63 N., R. 13 W.

North 2,000 paces from southeast corner sec. 3, T. 63 N., R. 13 W.

On east shore of large lake in T. 62 N., R. 14 W., just south of the east-west section line between secs. 25 and 36.

Another area is that occurring 1,650 paces north of southeast corner sec. 20, T. 63 N., R. 10 W. Here the tuffaceous rock has been sheared and where most schistose, with the schistosity striking N. 70° E., black jasper has been infiltrated.

EVIDENCES OF VOLCANIC CHARACTER.

Beginning about 1,500 paces north of the southeast corner sec. 3, T. 62 N., R. 12 W., and extending south along the section line to the quarter post, there are numerous exposures of dark-gray to green rocks which have irregular lines running through them, and possess a more or less perfectly preserved amygdaloidal and ellipsoidal structure. The lines referred to are thought to be flowage lines. These, in connection with the other structures mentioned, seem to be fair proof of the volcanic character of the rocks. These volcanics are penetrated by dikes of granite which vary in size from very small ones an inch or more in width to some having a width that is measurable by yards. The rocks themselves are imperfectly schistose, and may well be called amphibole- and mica-schists. The rocks in this locality represent one of the passage phases between the normal greenstones on the one hand and the amphibole- and mica-schists on the other, which, when close to the main mass of the granite, show none of the volcanic structures that enable their original character to be easily determined here. This passage from the normal greenstones through the amygdaloidal and ellipsoidal green schists to the normal schists next to the granite can be seen still better just north of the quarter post between sec. 19, T. 62 N., R. 12 W., and sec. 24, T. 62 N., R. 13 W., and also along the quarter line in the southeast quarter of sec. 24, T. 62 N., R. 13 W. At this last locality we pass from the granite into an area in which the schists and granites are most intricately mixed. The schists occasionally still possess an imperfect amygdaloidal structure. To the north we soon pass from very schistose greenstones to those which are only slightly schistose and in which amygdaloidal and ellipsoidal structures are well developed.

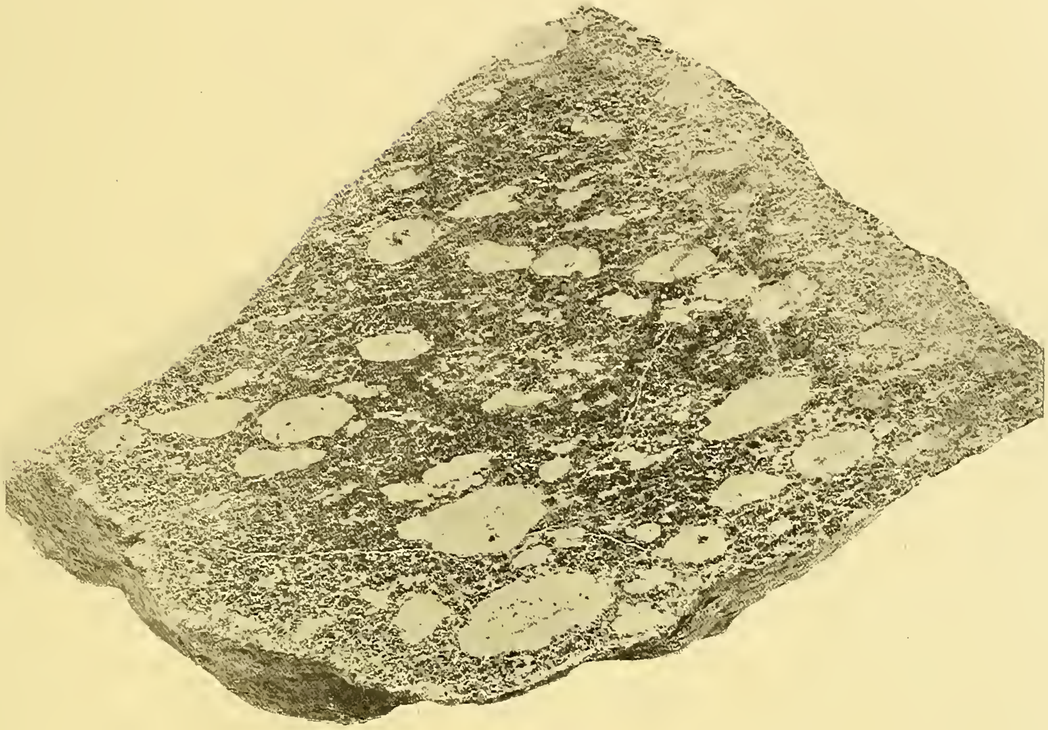
The ellipsoidal structure and the presence of spherulites, found most frequently in association with these ellipsoids, have been referred to as common features of the greenstones. Greenstones possessing both of these characters occur very commonly in large exposures throughout sec. 10 and the west half of sec. 11, T. 63 N., R. 10 W. They can be very clearly seen at a number of the exposures here, especially on one about 200 paces north and 1,000 paces west of the southeast corner of sec. 10, T. 63 N., R. 10 W. Here the greenstone is separated into large ellipsoids and the spherulites are arranged in concentric circles within the ellipsoids. The smallest spherulites occur near the periphery of the ellipsoids; the largest, 3 inches in diameter, occur nearer the center. These large spherulites show their radial structure in sections on the weathered surfaces of the rock. Some of them now consist of a chloritic mineral having a dark-green color and a silky luster. In most cases they are lighter colored, and the mineral constituting them is feldspar. The interference of the spherulites with one another in the process of growth is very prettily shown in many places. Very rarely are they perfectly round. In most cases they have interfered with each other, and while in some places nearly perfect spherulites may be observed, they are most commonly irregularly rounded and surrounded by others which have the form of segments of circles. It is evident that they did not all begin to form at just the same time or else their rate of growth was not just the same, for if their origin were simultaneous and their rate of growth equal we would get in cross section through such masses a structure resembling that of a honeycomb. These spherulitic greenstones are both fine and coarse grained, the ellipsoidal and spherulitic portions being continuous with the nonellipsoidal and nonspherulitic greenstones. It would seem that the ellipsoidal and spherulitic portions of the greenstones represent the surface of greenstone lavas which are to be considered as effusive sheets or flows. These greenstones are cut by dikes of granite-porphyry.

One mile north of North Twin Lake, at the northeast corner of sec. 12, T. 63 N., R. 10 W., these ellipsoidal spherulitic greenstones continue from south of Jasper Lake in almost continuous exposures eastward along the south section line of sec. 6, T. 63 N., R. 9 W., almost as far east as the south quarter post of that section. Here the ellipsoids reach a diameter of 3 to 4 feet and some of them are solid masses of spherulites, each spherulite showing its radial structure very beautifully on the weathered surface.

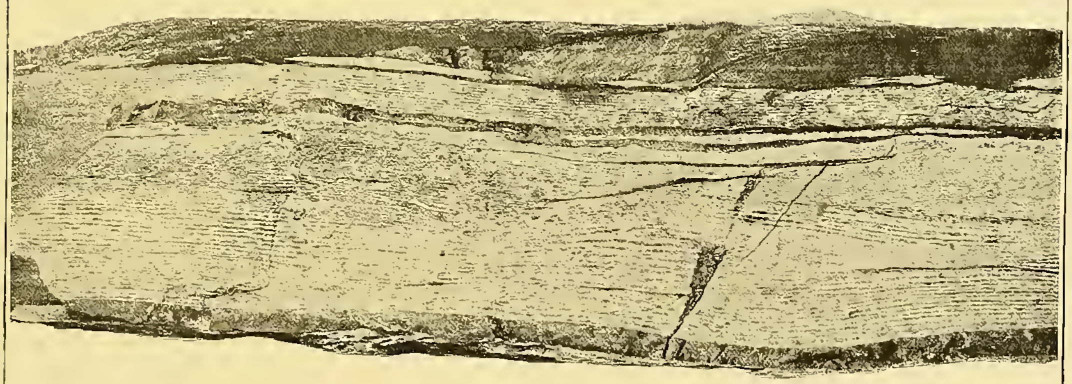
About 400 paces north, 100 paces west from the southeast corner of sec. 35, T. 62 N., R. 14 W., interbedded amygdaloidal and ellipsoidal basalts occur. They are all somewhat schistose. As we continue southward studying the exposures, we find that they show an increasing degree of metamorphism. They finally become amphibole- and mica-schists and gneisses, and but for the presence of the elongated ellipsoids and the amygdules, filled with chlorite and pinkish quartz, one could not be sure, from the field study, of their igneous origin. The rocks in this locality resemble in a striking degree the crystalline schists occurring in the vicinity of Bone Lake[a], in the Crystal Falls district of Michigan.

It has been stated repeatedly that certain of the greenstones possess an amygdaloidal structure, and that with these tuffs are associated. These facts have been cited as evidence of the volcanic nature of the greenstones. Such associated and presumably interbedded tuffs and amygdaloidal and porphyritic greenstones are very well exposed upon the west and northwest slopes of a high hill in the northwest quarter of sec. 19, T. 64 N., R. 10 W. Here the greenstones, which are both fine and coarse grained,

[a] The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey Vol. XXXVI, 1899, pp. 148–152.



(A)



(B)

A. AMYGDALOIDAL GREENSTONE (METABASALT).
B. MAGNETITIC CHERT, SHOWING POSSIBLE LINES OF FALSE BEDDING.

The bands of brilliant red jasper commonly show lines similar to these, but without the irregularities indicative of false bedding.

are dotted with abundant amygdules. In some instances amygdules are scattered over large areas. In other instances they are collected chiefly along certain lines which run about northeast. The individual lava flows could not be distinguished. The amygdules are now oval, with the long axes of the ovals parallel with the schistosity of the rocks, which trends N. 60° E. The amygdules range from very small ones to others which are 3 inches long and three-fourths of an inch across the shortest diameter. The accompanying illustration, Pl. V, *A*, is a reproduction of the polished surface of one of these metamorphosed amygdaloidal basalts. The rock is now an amphibole-schist, and but for the presence of the amygdules and its associations in the field it would not be recognized as a basic lava. These greenstones are cut by dikes of granite as well as by narrow dikes of basic rock.

The ellipsoidally parted greenstones are well exposed in the west half of sec. 17, east half of sec. 18, northeast quarter of sec. 19, and northwest quarter of sec. 20, T. 63 N., R. 9 W. The ellipsoidal parting and amygdaloidal characters of these rocks show clearly their identity with the Ely greenstone in other parts of the district. The ellipsoids vary in size considerably, and the matrix between them varies from one-half inch to 2 inches in thickness. This matrix has been silicified to a considerable extent, and in places appears very much like a black chert. The rocks have been extensively metamorphosed. This metamorphism is probably due largely to the effects of the Keweenawan gabbro, which at present is separated from the greenstone by the width of the Kawishiwi River. Formerly, however, the gabbro unquestionably overlaid the greenstone to the north of the river. The greenstone is cut by a number of dikes of basic rocks varying in width from a few inches to 30 feet. The dikes are dolerite and camptonite (?).

METAMORPHISM OF THE GREENSTONES.

The greenstones of the Vermilion district have been extremely metamorphosed by the intrusion of younger rocks, as well as—perhaps chiefly—by the intense folding to which they have been subjected. The oldest rocks, the Ely greenstones, have naturally been most metamorphosed, since they have been subjected not only to all of the folding which affected the younger rocks, but to previous metamorphic action.

The following description of an area on the portage between Wind and Moose lakes makes clear the difficulty which one experiences in attempting to discriminate between these greenstones and some of the rocks that are associated with and derived from them. The rock on the north side of the high ridge overlooking Wind Lake is undoubtedly a green schist derived from the Ely greenstone. It is broken by diagonal joints running in two directions, lines bisecting the acute angles of the rhomboids formed by the intersection of these joints being parallel to the strike. The minute diagonal fractures have been largely cemented by some material, as is shown by ridges that run along the weathered surfaces. The rock is veined with white quartz, but there is no definite banding except that produced by this material which has filled the fractures. There is no appearance whatever of pebbles in the rock. The schistosity is very strongly marked. Along the schistosity there are numerous fine quartz veins and some fractures filled by other materials, so that the rock shows a fairly distinct banding parallel to the schistosity.

South of this green schist there is a peculiar rock which shows very fine banding along the schistosity, as does the green schist above described. This banding does not seem to be due to secondary cementation, but apparently results from the mashing of originally heterogeneous material. On weathered surfaces of this rock that lie transverse to the schistosity there are obscure roundish or elliptical spots having their long directions parallel with the trend of the schistosity. These roundish spots are presumably mashed pebbles. They are very numerous, and increase in distinctness as one passes southward from the contact, and within a distance of 30 or 40 feet the rock assumes a distinctly conglomeratic appearance. When the rock is split the pebble-like masses are seen to be greatly extended in the direction of the schistosity. These masses are several times longer in the direction of the dip than along the strike, and from two to ten times as broad (along the strike) as they are thick. In these respects the rock is identical with the remarkable schist conglomerates of Vermont described by Hitchcock[a] in 1860.

In the conglomeratic rock at Wind Lake the regular system of fractures spoken of as occurring in the mass first described—the green schist adjacent to the conglomerate—are not present, at least with any such regularity,

[a] Geology of Vermont, Vol. I, 1861, pp. 28–42.

although there are irregular diagonal fractures wider apart. It seems as if there had been distributive movement about each pebble-like area, so that in this way readjustment occurred largely in the softer matrix-like material rather than in the regular fashion shown in the homogeneous rock to the north. These facts lead to the conclusion that the southern part of the ledge is decomposed, much mashed, detrital material derived from and resting upon homogeneous schistose material. Here it is rather difficult to draw the dividing line between the Ely greenstone and the conglomerate derived from it. At other places, where the mashing has not been so extensive and where the pebbles are far more distinctive, and especially where the rock contains pebbles of jasper and granite as well as of greenstone, the line of separation can be much more readily drawn.

Indeed, a little farther southeast, along this same trail—that is, on the Wind Lake–Moose Lake trail—a perfectly distinct conglomerate occurs which consists predominantly of greenstone pebbles and bowlders, some as large as 3 feet in diameter, but which contains many associated granite pebbles. From the repetition of different zones of conglomerate occurring on this portage it would seem that the rocks had been very intricately folded here and that the several different zones are really a single zone repeated as a result of the close folding.

In the southeast quarter of sec. 18, T. 62 N., R. 13 W., exposures are pretty numerous, and one finds here good opportunities for studying the transition from the greenstone, with ellipsoidal parting here and there, to the amphibole-mica-schists. These schists occur in their best, most typical development in close proximity to the Giants Range granite, which, as has already been stated in detail elsewhere, is considered to be the cause of their existence. In all such cases the farther one goes from the contact the less altered are the greenstones found to be, whereas the nearer the contact the more intricately are the greenstones cut by the granite dikes, and the more nearly they assume the characters of typical schists. The same observations, pointing toward the production of the schists from the greenstones by the intrusion of the granite, may be made at many places along the boundary between the granite and the greenstone, extending from sec. 31 northeastward through secs. 32 and 29 into sec. 28, all in T. 62 N., R. 13 W. At numerous places along this line the hornblende-schists still possess the ellipsoidal and less commonly the amygdaloidal characters of the unaltered greenstones. In some places the vesicles are half an inch in diameter, and their character is undoubted. Most commonly these are filled, and the amygdules are very prominent, though in other cases the amygdules have been weathered out. Not infrequently faint lines of somewhat lighter color than the main mass of the rock may be observed crossing the exposures diagonally to the schistosity. These lines seem to be most common where the amygdaloidal structure is most noticeable, and they appear to be the traces of flow structure in the lavas.

In the southeast quarter of sec. 16, T. 64 N., R. 9 W., just northwest of the southwestern end of Newfound Lake, there is a high hill, bare over a great portion of its surface, consisting of the Ely greenstone cut through and through by the granite of Basswood Lake. In some places the two rocks are present in about equal amount, though in general the greenstone predominates. The greenstone has been so much metamorphosed by the granite that it would be more accurately classed as an amphibole-schist. In many places the structural peculiarities of the Ely greenstone may be observed. This hill affords a good opportunity for study of the relations between the granite and the schist, and especially for observing the general characters of the amphibole-schists. Moreover, the fact, already stated, that the greenstone does not consist of a single rock, but of a complex, is clearly shown by the presence of a coarse, much metamorphosed dike of dolerite which cuts the schist and includes it and which in turn is cut by the younger granite.

SECTION III.—SOUDAN FORMATION.

The Soudan formation, a division of the Archean, lies above and is mainly younger than the Ely greenstone. It contains the important iron-ore deposits of the district and is well developed and exposed at the town of Soudan, where are located also some of the most important mines of the district.

OCCURRENCE AND CHARACTER.

DISTRIBUTION.

The iron-bearing formation begins 10 miles east of the western limit of the district as outlined in this report, and can be traced eastward for many miles, the easternmost occurrence seen being a very limited exposure south of Moose Lake, in sec. 4, T. 63 N., R. 9 W. However, the same formation occurs just north of the boundary in Ontario, and is known to continue northeastward for many miles within Canadian territory.

The Soudan formation has its greatest development in the western part of the district, the most prominent areas extending from Tower, on Vermilion Lake, in T. 62 N., R. 15 W., on the west, to Fall and Garden lakes, in T. 63 N., R. 11 W., just a few miles east of the well-known town of Ely, on the east.

The formation is most notably exposed in areas lying about midway between the north and south limits of the district. At Tower and Soudan it underlies broad areas and forms the prominent topographic features known as Tower, Lee, and Soudan hills, and Chester, or Jasper, Peak. Other fairly large areas occur in a belt just north and east of Ely, in sec. 25, T. 63 N., R. 12 W., and in sec. 30, T. 63 N., R. 11 W. North and south of and between the areas mentioned, the formation underlies rather narrow belts trending east-northeast to west-southwest. Each of these belts is made up of a series of narrow bands of the iron formation, interbedded in some cases with small quantities of fragmental rocks and intimately associated with the Ely greenstone and the late intrusives, which cut through both the Ely greenstone and the Soudan formation. As shown on the maps in the accompanying atlas, some of these belts, especially those near the center of the western part of the district, can be followed for a number of miles east and west; one was traced for 16 miles. Others are very much shorter, having been traced for only a few miles, and these small areas grade down to those which are mere patches, a few inches or feet across and a few feet or paces in extent—that is, along the strike. However, it is believed that all of these, from the largest to the smallest, with the exception possibly of certain small vein-like masses which will be mentioned later, are parts of one general formation, now separated from one another by folding and erosion.

A glance at the maps will show that the areal distribution of the Soudan formation is closely connected with that of the Ely greenstone.

EXPOSURES.

One would be inclined to think, judging from the resistant nature of the rocks constituting the iron formation, that it would be well exposed throughout the district. Such is, however, very far from the case. Except in a few places, notably at Tower, Lee, and Soudan hills and Jasper Peak;

in sec. 25, T. 63 N., R. 12 W.; sec. 30, T. 63 N., R. 11 W.; secs. 3 and 4, T. 61 N., R. 15 W.; secs. 7 and 8, T. 62 N., R. 14 W.; sec. 6, T. 62 N., R. 14 W., and sec. 1, T. 62 N., R. 15 W.; the exposures are very poor. But the fact that the exposures of the iron formation are scarce and small in some localities does not necessarily mean that the formation at such places is not now or may not become in the future of very great economic importance. For example, the immensely valuable iron deposits at Ely, extending from the Chandler mine on the west to the Savoy on the east, occur where jasper exposures are remarkably few.

In the belts traced through the district the exposures are small and discontinuous, both along and across the strike, and this would make it impossible to trace out any horizons in the iron-bearing formation, even if they could be determined, but, owing to the uniformity of the formation, such horizons can not be fixed. In making use of the accompanying maps it should be clearly understood that the colors or patterns indicate merely that the iron formation has been found in the areas so colored. The limits fixed do not necessarily imply that the area is underlain wholly by the formation, for, as has already been intimated above, in many instances exposures of greenstone, equally as numerous and as large, occur in these belts in intimate association with the jaspers. With these occur also younger intrusives, which cut through them. In fact, it is impracticable to say which of these two kinds of rock preponderates in many of such areas. The iron-bearing formation certainly does preponderate in a number of the well-known areas which will at once occur to those acquainted with the district—for example, on Tower and Lee and Soudan hills, Jasper Peak, ridge in sec. 25, T. 63 N., R. 12 W., and ridge in sec. 30, T. 63 N., R. 11 W. The above statement will hold true, however, on the whole, for the smaller belts. The belts outlined represent the possible ore-bearing areas, and such areas having once been outlined as closely as possible by the geologist, it then remains for the mining companies to make more detailed studies of them than it was possible for the members of the Survey to make in the limited time at their disposal.

In the course of the field work the occurrence of the iron formation has been reported from various localities, but search failed to reveal exposures in these places. It is highly possible that in the future other areas than those which are outlined on the accompanying maps will be found, but it can be confidently stated that they will in all cases be small and presumably of very slight importance.

TOPOGRAPHY.

The amount of the iron formation in the district is relatively so small that it can scarcely be said to have had any great effect upon the general topography. In those areas where it is best developed it does influence the topography very materially. As the result of the resistant character of the jasper, which is the predominant rock in the formation, strongly marked hills persist where it is present in large quantity. Of these, the most striking are Lee and Tower hills, Jasper or Chester Peak, the hill forming the prominent northeast point of Stuntz Bay, and the hills in sec. 7, T. 62 N., R. 14 W., and in sec. 4, T. 61 N., R. 14 W.; also the prominent ridge extending through sec. 25, T. 63 N., R. 12 W., and sec. 30, T. 63 N., R. 11 W. In the various belts containing the iron formation the jasper very commonly occupies minor prominences, the low ground between being occupied presumably by the associated greenstones and sediments.

STRUCTURE.

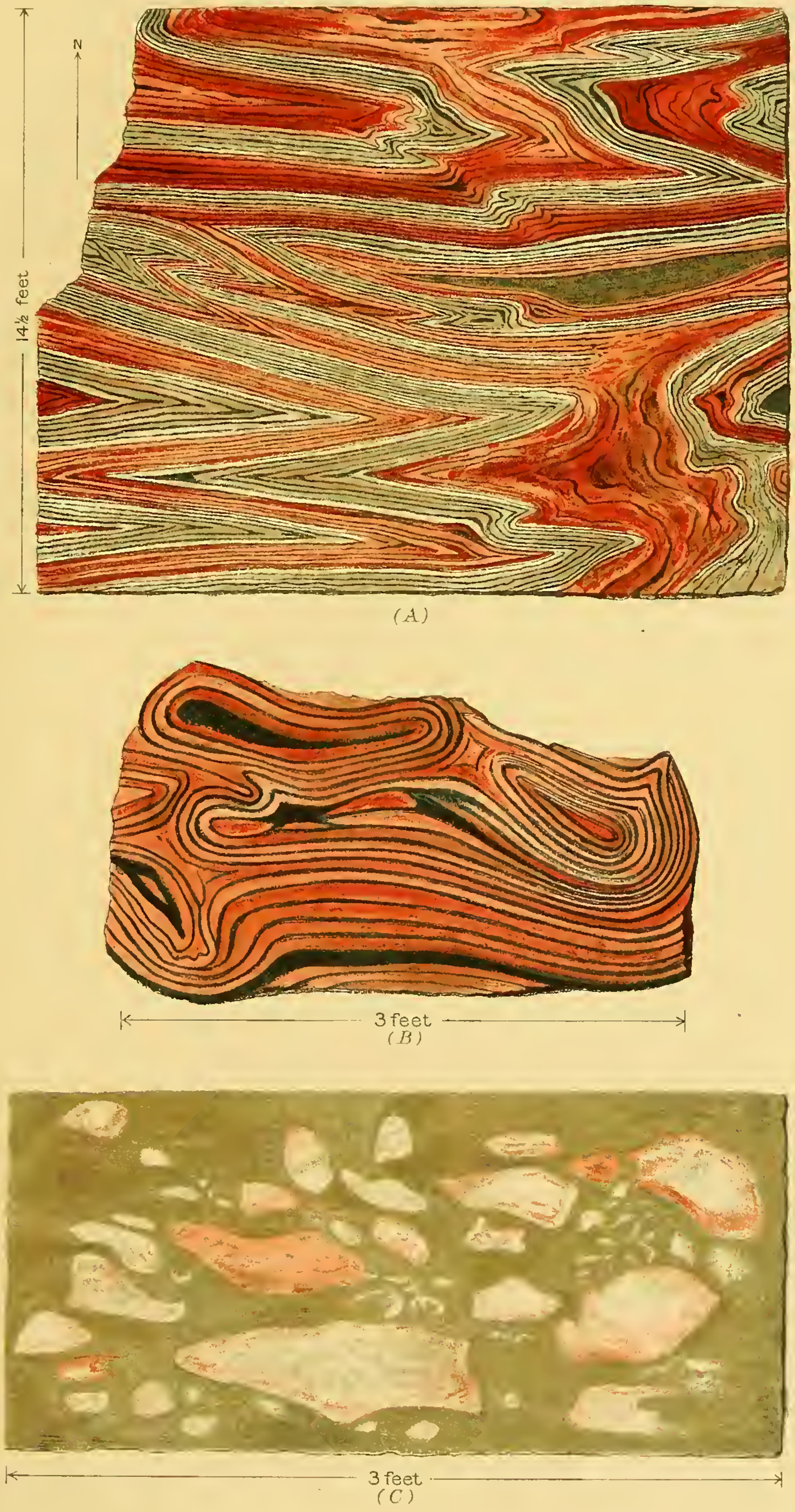
The iron-bearing Soudan formation being the oldest sedimentary formation in the district has been subjected to all of the orogenic movements which have occurred in the district since its deposition. Since there were several of these movements, and since the forces producing them were very intense, the formation has been most intricately folded. It is indeed difficult to describe or represent the intricacy of the folding which it exhibits upon nearly every exposure of any size.

On a large scale the formation has been folded into anticlines and synclines, and its structure is now shown to a certain extent by the topography. Thus, for example, the prominent hills—Lee, Tower, and Soudan—are great anticlines with minor synclines and anticlines superimposed upon them, whereas Jasper Peak is situated at the end of a syncline, and on its western and southern sides shows very prettily the jasper folded into a series of rolls pitching a little to the east of north. It is also highly probable that some of the east-west trending belts of the iron formation are to be considered as synclines of jasper infolded in the older greenstone. Upon the more prominent anticlines and synclines numerous minor folds are superimposed, giving the intricacy of structure already referred to. It is of interest to note in connection with this remarkably close folding of the jasper—some of the bands are actually folded upon themselves within a radius scarcely greater than the width of the belt—that the jasper for the most part has not been very much fractured. This is very clearly indicative of the great depth at which this formation lay at the time the folding took place. This close folding without fracture can be explained only by assuming that the rocks were under such great pressure that they acted practically as plastic bodies. North of Fall Lake the close folding of the jasper is shown in one place where bands 4 to 5 inches in width have been turned so sharply that the two ends are now only 1 foot apart, and here the jasper, usually considered a very brittle substance, shows no indications of fractures, but has comported itself as a viscous material.

Pl. VI, *A* and *B*, reproduced from sketches made by W. N. Merriam in the field, from actual exposures near Soudan, shows very well the extreme intricacy of the folding.

Both the longitudinal and the cross folding of the iron formation is composite; that is, superimposed upon the major folds in each direction are folds of the second order, and upon these are folds of the third order, and so on down to minute plications. The pressure has been so great as to give all variety of minor folds, including isoclinal and fan shaped. Moreover, these varieties of folds may be seen almost equally well on a ground plan or on a vertical cross section. They are beautifully shown at various places about Tower and Ely, but perhaps the most extraordinarily complex folding seen is that at the west end of the large island in the east part of Emerald Lake. Figs. *A* and *B* of Pl. VI, which are upon the whole representative of the district, show that the folding, notwithstanding the extremely brittle character of the rock, was accomplished without major fracture. The deformation, therefore, is deformation in the zone of rock flowage, and no better instance is known to the writer of this kind of earth movement. Frequently a solid belt of jasper is bent back upon itself within a radius of its own width with no sign of fracture.

Though the folding is so complex as to give even fan-shaped folds, the turns are ordinarily round rather than angled, thus differing from those acute-angled folds frequently seen in the Menominee district. The roundness of the folds is well illustrated in the figures.



JULIUS BIEN & CO LITH N.Y.

FOLDED AND BRECCIATED JASPER OF THE SOUDAN FORMATION.

The Vermilion district, therefore, appears to be one of the best regions in the world to illustrate complex folds, or folding in two directions at right angles to each other, and the formation that best exhibits this folding is the Soudan. This is due to the very marked banding of that formation, by means of which the position of bedding is readily determined, and to the fact that for the most part it does not take on any secondary structure. Furthermore, it frequently is found in contact with the Ely greenstone, which also gives the pitch of the cross folds.

This remarkably complex folding partly explains the distribution of the Soudan formation with reference to the Ely greenstone. Naturally, where the formation is thick it is found along the border of the greenstone. However, since upon the major folds are superimposed secondary and tertiary folds, numerous patches of the jasper occur in the greenstone. Moreover, because of the cross folding, these patches may be very narrow at one place, widen out very rapidly so as to make a thick formation, and again narrow. When the extraordinary complexity of this folding is understood one has only to premise an erosion extending to different depths in the Soudan formation before the Lower Huronian was deposited in order to see how in the greenstone the jasper may range in size or extent from patches a few feet in width and length, to the great continuous formation about Tower and Ely. Moreover, such premise fully explains the extraordinary variation in width of the jasper belts at some places and their persistency and uniformity at others.

Occasionally there is associated with the iron formation and interbanded with the jasper some bands of slaty material. In places the amount of this slaty material is so great that where folding has taken place a slaty cleavage has developed in these layers. This cleavage, however, does not pass through the bands of iron oxide or chert. These bands with the slaty cleavage afford excellent opportunities for making observations upon the relations of cleavage to the direction of pressure. In these bands this development of slaty cleavage is seen to obey the laws of slaty cleavage, as explained by Van Hise.[a] Pl. VII, a representation of a specimen taken from the folded jaspers, shows this cleavage so clearly that textual explanation is scarcely needed.

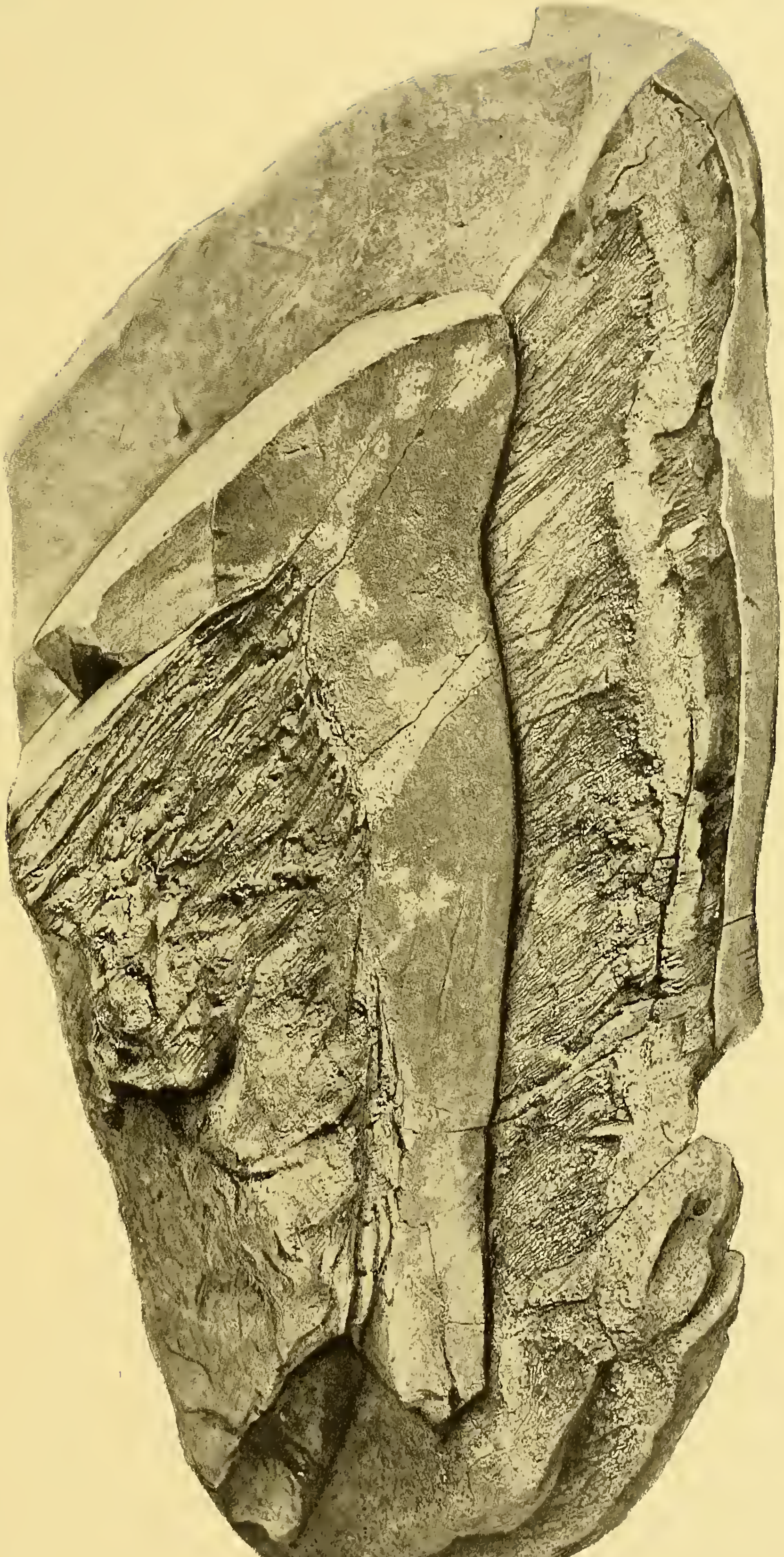
---

[a] Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Pt. I, 1896, pp. 363-369.

Even where the bands of slaty material in the rocks are not more than one-fourth of an inch across, the slaty cleavage is perfectly developed and stops abruptly at the adjacent more brittle cherty material. Thus we have in this phase of the iron formation numerous layers showing good slaty cleavage alternating with others in which it is absent. The slaty cleavage is in such position in reference to the plications as to show that it developed normally to the pressure. The lack of parallelism of the cleavage upon opposite sides of the folds beautifully illustrates the principle that on anticlines the cleavage on opposite sides of folds diverges downward and on synclines converges downward. These alternating slate and jasper bands are well shown in the so-called "Burnt Forties" adjacent to Vermilion Lake.

While usually deformation has taken place without fracture, the jasper is sometimes brecciated. We sometimes find very pretty "reibungs" or friction breccia formed of the jasper fragments cemented together by vein quartz. Not uncommonly such a brecciated zone occurs near the base of the iron formation, between it and the lower-lying greenstones, and is thus clearly the result of movement along the plane separating the two kinds of rocks. In such instances, the jasper, being the more brittle of the two rocks, forms the angular to partly rounded fragments of the breccia, whereas the greenstone, in some cases at least, is found to have been forced in between the jasper fragments and to play the part of a matrix cementing the breccia together (Pl. VI, *C*). The plane of brecciation being more open. has been especially favorable for the free movement of underground water. Similar brecciated zones at the base of the jasper—that is, between it and the greenstones—due to movements along this plane, occur near the west end of Emerald Lake, just north of the international boundary, on the point that projects eastward from the south shore of this lake. Consequent upon this brecciation there has been infiltration of various substances, especially of quartz and iron oxide subsequent to the formation of the breccia, which also tends to cement the fragments together and likewise to discolor the rock.

On the east end of Lee Hill, on the south side of the old North Lee mine, there is a brecciated zone in which the above-mentioned conditions can be observed. It is further very noticeable here—and the same thing may be seen at other places—that the fragments are frequently cemented together by very pure hematite, and when there were favorable cavities of sufficient size subordinate bodies of very high-grade ore were deposited.



FOLDED JASPER AND SLATE, SHOWING SLATY CLEAVAGE DEVELOPED IN SLATE BANDS.

In spite of the intricacy of the folding of the iron formation, it has been possible to determine that in general the axes of the major folds strike east-northeast to west-southwest, the clearest instance of such a large fold being the syncline at Ely. The dip of the axial plane of these folds appears almost without exception to be steep to the north, indicating that the closeness of the folding has been very great and overturns are common results of this. It is interesting to find that this axial plane has been subject to torsional movement, as in the case of the plane of the Ely syncline. This upon the west end dips to the north, but underground explorations at the east end show that it has here a reversed dip to the south.

PETROGRAPHIC CHARACTERS.

MACROSCOPIC CHARACTERS OF THE FRAGMENTAL PORTION OF THE SOUDAN FORMATION.

The Soudan formation may be divided into a fragmental series of sediments and into the iron formation proper, whose origin is not distinctly clastic.

The clastic portion of the formation will be described first, for the reason that it always underlies the iron formation proper. The very few occurrences of these clastic sediments are so widely separated from each other areally that it is impossible to say that they all belong to the same beds, although they everywhere bear the same relation to the iron formation. And in this connection it must be borne in mind that there is a possibility that the different bands of the iron formation are not of exactly the same age, but represent stages of deposition of slightly different age, although all of the same general period. The sediments of the clastic division of the iron formation are grayish green and black in color, and consist of a conglomerate at the base, grading upward into the finer-grained deposits. The conglomerate lies next to the greenstone, and consists—both matrix and pebbles—of the material derived therefrom and some pebbles of vein quartz. The finer sediments are chiefly finer material of the same character, derived from the same source. The exception to this statement would be certain soft, black, graphitic slates which are found associated with the jaspers. Such may be observed, for example, upon the westernmost exposures of Lee Hill, just back—that is, north—of the houses of Tower. A somewhat similar graphitic slate is found on the southern slope of Soudan Hill, about 200 yards northeast of No. 12 shaft, which is northwest of the

Minnesota Iron Company's warehouse. The presence of these graphitic slates with the iron formation probably accounts for the large masses of graphitic rock on the twelfth level in No. 8 shaft at Soudan. There is a mass of this graphitic rock 10 feet long and from 6 to 8 feet thick completely lying in the soap rock. It was cut in a third dimension for 11 feet, and how much farther it may extend in this direction is unknown. This graphitic rock was tested, it is said, by Mr. John H. Eby, sometime mining engineer of the Minnesota Iron Company, who reported it as graphite.

These clastic sediments are interbedded with the jasper and other materials constituting the iron formation proper. Toward the iron formation the bands apparently become more frequent, and the clastic sediments decrease in amount, and there is thus a gradual transition into the iron formation proper.

The lower clastic portion of the formation is by no means characteristic. It is rarely present, and when present is very thin. In one place about 40 feet of sediments, chiefly conglomerate, were seen, but the exposures were so poor that it was impossible to tell whether the beds were duplicated by folding or not. It is possible that some fairly wide areas separating jasper exposures from greenstone exposures may be underlain by the clastic formation, but this is not probable, for the practical absence of the formation, which is fairly resistant throughout the district, shows that it must have been very subordinate. Yet, in spite of its subordinate position quantitively, this clastic portion of the formation is of great stratigraphic importance, as no matter at how few places it has been found or how thin it may be, it nevertheless is clear proof of a very important change in conditions, marking the transition from the period of volcanic activity in which the greenstone had its origin to the period of sedimentary deposition in which the Soudan formation was laid down.

MICROSCOPIC CHARACTERS OF THE FRAGMENTAL PORTION OF THE SOUDAN FORMATION.

The conglomerate and normal fine-grained sediments, belonging for the most part below the iron-bearing formation proper, show nothing under the microscope which is worthy of detailed description. The conglomerates are clearly recognizable in the field as clastics, and under the microscope one can distinguish the extremely altered greenstone fragments and the matrix derived from the greenstones, both consisting now largely of actinolite, chlorite, and epidote, with quartz. As the sediments get finer the clastic characters disappear as the result of the extreme alteration, and one can only surmise the mode of origin of these rocks by their intimate association with and gradations from the coarse clastics, and, when no gradation is visible, by the presence of banding and false-bedding lines. The microscopic examination shows these sediments to be made up of chlorite, actinolite, epidote, sericite, sphene, quartz, carbonaceous material (graphite), and some iron oxides, in various proportions, so that these metamorphosed slates vary from absolutely black, greasy-feeling, graphitic slates to dark-green and fairly light greenish-gray rocks. The graphitic slates consist essentially of graphite and quartz in exceedingly fine grains and in some cases in very small quantity. In one specimen the place of the quartz seemed to be taken by feldspar, which is altered to sericite, so that the sediment consists of graphite and altered feldspar.

MACROSCOPIC CHARACTERS OF THE IRON-BEARING FORMATION PROPER.

The iron-bearing formation proper (that is, that portion in which the ore bodies occur) consists of cherts of various colors—green, white, yellow, black, and purplish—red jasper, carbonate-bearing chert, slaty rock, showing in some cases intimate association with the clastic formation proper, grünerite-magnetite-schist, hematite, magnetite, and some pyrite. To the formation as a whole the miners and prospectors apply the name "jasper," although only a portion of it falls strictly under this designation. These various kinds of rock occur in bands of varying thickness, rarely exceeding 5 or 6 inches, and commonly in extremely thin laminæ. Usually the individual bands appear to be homogeneous. Occasionally there is a banding within the bands, which is due to the arrangement of the mineral constituents. In one place such a banding simulated the false bedding of normal clastic sediments (Pl. V, *B*).

The alternate bands of material of different color combined with the complicated folding make the formation a very striking object, which on exposures almost always attracts the attention of the traveler, even if he is not accustomed to closely noticing rocks.

The hematite, besides being interbanded with the other materials, also occurs very frequently in masses of variable size and shape. These constitute the ore deposits of the district, and will be considered under a separate head. The bands are not arranged in any definite order, but alternate with one another, giving a very regular ribbon or banded structure. All the colored cherts have the white as a base, the difference in color being due chiefly to the presence of the iron, either in the form of magnetite, hematite, or limonite, or as a combination of these. The black cherts, frequently called black jasper or hungry jasper, always contain a large quantity of magnetite, to which they owe their color. The brilliant-red jasper owes its color, as is well known, to the thin transparent plates and minute specks of blood-red hematite. The color of the brown cherts is due to the limonite. The colors of the other varieties—gray, brown, and ocherous yellow—depend on the mixtures of the above oxides or of their alteration products. Of somewhat rarer occurrence is the slightly greenish and grayish chert, which, although subordinate in quantity, is important in reference to the genesis of the iron-bearing formation. This chert contains a considerable amount of iron carbonate and grünerite, to which it owes its color. These chert bands become yellow and brown on weathering, on account of the formation of ocher by the decomposition of the carbonate and grünerite. The hematite and magnetite bands associated with the cherts are very rarely pure. On examining them it will be found in almost every case that the hematite bands contain varying percentages of magnetite, and vice versa. With these of course one is always sure to find a variable quantity of quartz. Iron pyrite is mixed with these various rocks in small amounts, but it is not known to occur in large quantity in this district.

The most intimate relationship exists between the various above-mentioned members of the iron-bearing formation proper. Gradual transition from one into another may be traced. Near the west end of Tower Hill, in following the strike of the rocks, one finds the jasper becoming less brilliantly colored and grading with continuous exposures into the black magnetitic jasper. The iron formation has been folded, and as a consequence is traversed by more or less frequent fractures. These fractures have been filled by veins of quartz which run transverse to the banding in the iron formation. The smaller cracks have very commonly been filled by iron oxide that is in all respects identical with that occurring interbanded with the jaspers. The secondary nature of the oxide that fills the cracks is indisputably shown by this occurrence, and is strongly indicative of the secondary origin of that in the bands, the two probably being of contemporary formation. In studying the formation it was noted that two series of cracks had been formed in the jaspers, the older having been filled with vein quartz and the younger with hematite.

THE IRON ORES.

The upper part of the Soudan formation is in a strict sense the ore-bearing portion. Indeed, this is the iron-bearing formation which has given to the Vermilion district its great economic importance, since from this have been derived great quantities of the high-grade ore which has assisted materially in making the Lake Superior region the greatest single factor in the development of the iron industry of the United States and of the world. The ores of the Vermilion district comprise several varieties—massive, granular hematite, specular hematite, and insignificant amounts of magnetite and limonite. There are, of course, also all kinds of mixtures of these, showing gradational phases from one variety to the other.

The predominant ore is an exceedingly hard, massive, granular, steel-blue hematite. The specular ore occurs locally in small masses. The magnetite is obtained only in small quantities, and is intimately associated with the hematite. Occasionally small bodies of magnetite ore are found, not large enough to be of special value, or to warrant an attempt to obtain a grade of magnetite ore. Such occurrences are very exceptional. The limonite is very subordinate, occurring only associated with the hematite. There seems to be a general misapprehension as to the character of the ore in the Chandler mine at Ely, the greatest producer of the district. It is very commonly spoken of as a soft ore. This is, however, purely a relative term, in this case depending upon the brecciated condition of the ore, which enables it to be won with less drilling and with much less expenditure of high explosives than is required, for instance, in the Minnesota Iron Company's mine at Tower. The ore is found in an extremely brecciated condition by the miners, and this brecciation is taken advantage of and really increased by the method of mining employed. As a result of this more or less finely brecciated condition the ore is obtained to a great extent by the use of picks. The fragments of the breccia are, however, the same hard ore that occurs in the other mines of the district, but as a result of the brecciation, a great deal of very finely comminuted ore is associated with the larger fragments and occurs between them. The cause of the brecciated condition of this ore will be discussed more at length under the heading "Ore deposits."

The ores of the district are rendered impure by various mechanical mixtures of quartz, calcite, chlorite, iron pyrites, native copper, the oxide of copper (cuprite), and the carbonates (malachite and azurite). These copper ores are present in very small quantity, however, and are of chief interest on account of the fact that this occurrence of these minerals in association with the ores at Soudan is the first recorded from the Lake Superior region.[a] Mr. Pengilly informed the writer that native copper had been found in the Chandler mine several years prior to its known occurrence at Soudan. Quartz, calcite, chlorite, and pyrite occur locally, but in considerable quantity, and as a result large quantities of ore are thrown away in the attempt to get rid of these impurities. Good hand specimens showing these minerals can always be obtained from the dump piles and even the stock piles of the Soudan mines. The minerals occur along the walls of vugs of various sizes which exist in the ore bodies.

The iron content of the Vermilion iron ores, computed from cargo analyses made during 1899, varies from 60.47 to 67.37 per cent, and averages about 63.7 per cent. The phosphorus content varies from 0.04 to 0.131 per cent, and averages about 0.057 per cent. The silica content varies from 2.55 to 7.67 per cent, and averages 4.78 per cent. The water content varies from 1.04 to 7.956 per cent, and averages about 5.50 per cent. The ore bodies are of such importance that their origin, the occurrence of the ore in them, etc., will be considered in detail under separate headings.

The physical character of the ores is such as to make them much desired by the smelters for admixture with the softer, finer-grained ores. The ores are hard and are obtained in large pieces and run through crushers and

[a] The occurrence of copper minerals in hematite ore, Montana mine, Soudan, Minnesota; description of the occurrence, by J. H. Eby; study of the minerals, by C. P. Berkey: Trans. Lake Superior Mining Institute, Vol. IV, 1896, pp. 69–79.

broken. The following table, made by Mr. R. B. Green, in 1898, at the Minnesota Iron Company laboratory at Two Harbors, Minn., shows the coarseness of the Chandler and Pioneer ores of Ely. Ores from Soudan are, perhaps, even coarser.

Percentage of ore from Chandler and Pioneer mines, Ely, Minn., that passes through screens of specified mesh per inch.

[Determined in natural state after taking from cars and drying.]

Kind of ore.	Does not pass 8 meshes.	8 meshes to 20 meshes.	20 meshes to 100 meshes.	100 meshes.
Chandler ore (28 cargoes)	82.05	9.14	5.86	2.94
Long Lake ore, Chandler mine (13 cargoes)	76.99	10.94	8.08	3.98
Pioneer ore (23 cargoes)	77.50	11.00	7.08	4.42
Pilot ore, Chandler mine (2 cargoes)	65.65	13.93	11.44	8.97

MICROSCOPIC CHARACTERS OF THE IRON-BEARING FORMATION PROPER.

The iron-bearing formation proper consists of the various colored cherts, grünerite-magnetite-schists, hematite, magnetite, and limonite. With the iron-bearing formation proper, but in quantity very subordinate to the cherts, jaspers, and iron oxide, there occur some greenish to gray slates, and also graphitic slates. Upon close examination under the microscope these do not show evidence of their clastic character. False bedding would perhaps indicate their clastic origin, but no other evidence of this has been found other than their similarity to the slates above mentioned, which grade into the recognized clastics.

The white chert, in combination with various minerals which color it, forms the bases of the colored varieties of cherts already enumerated on page 181. When pure the white chert consists of quartz varying in size of grain from that which is minutely crystalline to that which is somewhat more coarsely crystalline. The grains are polygonal and generally more or less roundish. In one case, in a relatively coarse-grained chert, three quartz grains were observed which showed a roundish core outlined by a film of iron oxide, and beyond the iron oxide a zone of clear quartz. This secondary enlargement might possibly be taken as evidence of the clastic origin of the grains, but this structure is not sufficient evidence of such origin, and even if it were considered sufficient proof for the grains it would not be sufficient evidence to prove this origin for the surrounding cherts. A more or less perfect false bedding observed in some of these cherts (Pl. V, *B*) might also be considered the result of water motion. But this would not prove the cherts to be of mechanical origin, as we find this structure in sediments of organic origin also. The fine grains of quartz constituting the chert contain scattered through them minute crystals and specks of magnetite and hematite and areas of limonite. In some places these crystals are very small—mere dust as it were; in others they are of considerable size. At some places the quartz grains will contain very few of these dust specks; at others they are nearly full of them and appear almost opaque. The crystals of the iron oxides may occur at any and all places in these quartz grains, from the center to the periphery, and when the crystals are large they not infrequently extend from one quartz grain to another, running across the junction of the grains. In some cases these polygonal grains are outlined very distinctly by iron oxide, occurring either as a mere film or as a layer of considerable thickness. Instances were observed where the grains of quartz in the chert were heavily impregnated with particles of iron ore on the periphery, leaving but a small, fairly clear center. Other instances were observed where there was less of the clear central quartz present, and, in fact, there seemed to be all gradations from these cases up to those in which there was an opaque mass of ore giving but an occasional indication of the presence of quartz. These facts seem to show that the ore in these rocks is not primary, but is a secondary product which has been accumulated either in bands or in irregular masses as the result of the replacement of silica by iron oxide.

There is one variety of the chert which is interesting, for it seems to give a clue to the siliceous rock which has been replaced by the ore. This variety is the greenish carbonate-bearing chert to which reference has already been made. Under the microscope such cherts show up as finely granular aggregates of silica in normal rounded polygonal grains, but associated with the silica grains is a carbonate which occurs in rounded rhombohedra. The rounding of these grains is not the result of mechanical action. A study of the slides shows the alteration of the carbonate to limonite. A further change, resulting from dehydration, would produce a hematite-bearing chert, and in cases where the oxidation of the carbonate took place with access of insufficient amount of oxygen there would be produced magnetitic chert. In rocks containing a large proportion of carbonate and a relatively small proportion of chert we might thus get as a result of the alteration of the carbonate a ferruginous rock, possibly with alternate bands rich and poor in iron. These presumably served as a nucleus from which, by replacement, were derived the more ferruginous bands and ore deposits. Detailed descriptions of these processes have been given elsewhere by Van Hise,[a] and will not be discussed in this place. The presence of the limonite, hematite, and magnetite in the cherts gives us the varieties of the ferruginous chert, as it is commonly called—the red jasper and the black or lean, hungry jasper, respectively.

Associated with these cherts and ores are the grünerite-magnetite rocks. These are not present in large quantity. In places we find a green rock consisting essentially of chert with grünerite and but few crystals of magnetite; at other places there are rocks in which magnetite is the essential constituent with but little grünerite; and all gradations between exist. This grünerite is very nearly of the composition of the hydrated ferrous silicate which is so abundant in and forms such a conspicuous part of the iron-bearing rocks of the Mesabi range. This material has been described in detail in the monograph on this range by C. K. Leith.[b] Altered forms of this same material occur in the iron-bearing Gunflint formation at the eastern end of the Vermilion district. The grünerite may very well have been derived from this material by a simple process of dehydration, or it may have been produced from an iron carbonate by silicification, as it was in the Marquette district, as described by Van Hise.[c] Indeed, since, as is concluded later, on page 191, iron carbonate was the original rock of the iron-bearing formation, it is presumed that the grünerite was for the most part formed by the silicification of the carbonate.

In those rocks in which the grünerite occurs no traces have been found of the peculiar oval and globular structures so characteristic of the Biwabik and Gunflint rocks. The absence of these rounded bodies is not, however, conclusive evidence that they did not originally exist. These rocks have

---

[a] The Penokee iron-bearing series of Michigan and Wisconsin, by C. R. Van Hise; Mon. U. S. Geol. Survey Vol. XIX, 1892, p. 283 et seq. The Marquette iron-bearing series of Michigan, by C. R. Van Hise; Mon. U. S. Geol. Survey Vol. XXVIII, 1897, p. 402.

[b] The Mesabi iron-bearing district of Minnesota, by Charles Kenneth Leith: Mon. U. S. Geol. Survey Vol. XLIII, 1903, p. 101 et seq.

[c] The Marquette iron-bearing series of Michigan, by C. R. Van Hise: Mon. U. S. Geol. Survey Vol. XXVIII, 1897, p. 367.

been extremely altered, and with the recrystallization of the elements there may have taken place complete destruction of the original structures, with the exception of banding, which is still evident, and, in fact, this may have been further emphasized by the rearrangement of the constituents.

ORIGIN.

The banded structure of the iron-bearing formation is exceedingly regular throughout the district. It is difficult to say how persistent the individual bands are, however, for the outcrops do not allow them to be traced over very long distances. Most of the bands seen at a particular exposure persist entirely across the exposed surface. A few, however, run out to a feather edge even on small exposures, and thus disappear. The presumption is that all the bands feather out within a shorter or longer distance. This banding is so well marked and so eminently characteristic that from its presence alone one is fully warranted in making the statement that the structure of the formation is essentially that of a sedimentary rock. Furthermore, the composition and texture of the rocks making up the formation are such that we can assert with confidence that none of the members are of igneous origin. It has already been stated that in places the iron formation proper—that is, the interbanded iron oxides, cherts, and jaspers—overlie conformably a series of clastic rocks, beginning at the bottom with a conglomerate and grading upward into finer material, and also that we find similar fine clastic material interbanded with the iron oxides, cherts, and jaspers. This clearly indicates that the rocks of the iron formation are of sedimentary origin. The presumption is that the clastics were first formed; that there was then a period with changing conditions, during which the slates and iron-formation rocks were interbedded, and that finally the conditions controlling the deposition of rocks of the iron-bearing formation became more persistent when the original rocks of the iron-bearing formation were deposited. This enables us to explain certain characteristics of the contact between the greenstone and the iron formation which, in view of the known relations of these rocks, could not otherwise be explained. At a point 2,000 paces east, 700 paces south of the southeast corner of sec. 17, T. 62 N., R. 13 W., there is an exposure of jasper on the south side of massive greenstone. At this exposure there seems to be a gradation of the greenstone into the jasper. On the north side of the exposure the greenstone is massive, but as it nears the jasper it becomes more and more schistose, and with this increasing schistosity there is a more or less imperfect banding, brought about by an alternation of bands of the greenstone discolored with iron with those which are not so colored. Farther south the true jasper appears. Here apparently is a fine-grained mechanical sediment derived from and immediately overlying the greenstone, a deposit which is essentially indistinguishable from the greenstone so far as its composition is concerned, its mode of origin being indicated by the imperfect banding and the presence of ferruginous material. Here there is no well-marked clastic deposit between the greenstone and the iron formation, and this is one of the localities where the quiet conditions controlling the deposition of the iron formation had already set in, while in other parts of the district clastics were being formed. For instance, in sec. 10, T. 63 N., R. 10 W., west of North Twin Lakes, bands of the jasper lie parallel to the strike of the edge of the greenstone in contact with it, as though the banded rocks were a sedimentary deposit laid down upon it as a base. But no clastic sediments were found in this case between the jasper and the greenstone, their absence being due probably to the fact that here, likewise, the conditions were those of quiet deposition, during which no clastics could be formed. From the fact that the rocks of the iron formation are conformable with the clastic sediments near their contact one might be inclined to infer that the iron-formation rocks also are of mechanical origin. But microscopic examination, however, shows that the cherts and jaspers and ores do not possess the minute textures indicative of mechanical sediments, although one case has been noted in which three possibly clastic quartz grains were associated with the chert, thus showing that the conditions fluctuated from those suitable for the formation of clastic sediments to those giving rise to organic sediments, as shown also by the microscopic occurrence of interbanded clastics with the cherts.

In recapitulation it may be said that the banding possessed by the iron formation and the slaty bands associated with it, which show true sedimentary characters, and which were evidently originally of detrital mud, give the clearest proof of the sedimentary origin of the iron formation itself. The question which may next be raised concerning its mode of origin is whether it could not have been a chemical deposit. N. H. Winchell and H. V. Winchell, who have had excellent opportunities for studying the Minnesota deposits, have so construed them.[a] A condition which would admit of the precipitation from a sea of a rock as acid as a chert, consisting essentially of pure silica, followed immediately by the precipitation of rock as basic as the bands of pure iron ore, is so anomalous as not to be tenable. The only explanation which seems most nearly to meet and to answer the requirements of texture, structure, and composition is that the rocks are now in a very different condition, both chemically and physically, from what they were when originally deposited. Their present condition may be interpreted as due to secondary changes acting upon rocks of banded character.

The exact character of these original rocks is a question of much moment. As the source of the iron-bearing rocks of the Mesabi range Spurr has suggested an original glauconitic greensand, partly of foraminiferal origin. The green material, called by Spurr glauconite, has been carefully studied by C. K. Leith, and has been found to be not glauconite but a hydrous ferrous silicate without any potassium, and it has been called "greenalite."[b] Microscopic study of the rocks from the Archean iron-bearing formation of the Vermilion district has shown no evidence of the former existence of such foraminiferal rocks or glauconitic greensands; nor, indeed, has any rock been found which can be proved to be the original rock from which the ores and associated rocks have been produced. However, that kind of rock which approaches nearest to the supposed original rock is the cherty iron carbonate forming a part of the iron formation. This now appears to represent a stage in the process of metamorphism between the cherts and jaspers and ores on the one hand, and the relatively pure iron carbonate on the other.

The presence of this cherty iron carbonate in the Vermilion district, in association with the other members of the iron-bearing formation, offers also a striking analogy between this district and those on the south shore of Lake Superior.[c] In the various monographs upon the iron ranges in the United States portion of the Lake Superior region, Professor Van Hise has presented

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 547; Geol. and Nat. Hist. Survey of Minnesota, Bull. No. 6, 1891, pp. 105–111.

[b] The Mesabi iron-bearing district of Minnesota, by C. K. Leith: Mon. U. S. Geol. Survey Vol. XLIII, 1903, p. 115.

[c] Tenth Ann. Rept. U. S. Geol. Survey, pp. 396–397; Monographs U. S. Geol. Survey Vols. XIX, XXVIII, and XXXVI.

the proof in favor of his view that the cherty iron carbonate is the original rock of the iron-bearing formations. In the Vermilion district the iron carbonate is present in very small quantity, but it is significant that we find siderite in large quantity in the ranges east of this but in line of its strike, for instance near Port Arthur and in the Michipicoten district.

No proof of the supposition that a cherty iron carbonate is the original rock of the Soudan formation has been found in the Vermilion district. From the analogy of this with the other iron-bearing districts of the region it seems most probable that in this, as in the districts above referred to, the cherty iron carbonate was the chief original rock of the iron-bearing formation. In the monographs cited above, details are given which will enable the reader to follow the various changes which, by leaching and deposition, transform the cherty iron carbonate into chert, jasper, and ore.

While stress has been laid upon the formation of the jasper as the result of secondary processes acting upon an originally ferruginous rock, it must be stated that in certain places in the district the jasper doubtless owes its origin to processes of secondary infiltration. Such jasper occurs in vein-like form and in irregular bunches. It may occur also as the cement of the brecciated greenstones, and is found occasionally lying between the greenstone ellipsoids. The possibility that some of this jasper may be due to secondary action must of course be admitted. This is admitted, however, only for very small masses. These masses were probably formed by infiltration in openings in the greenstones, from above, during the time that the overlying cherty iron carbonates were being changed to the present condition of the iron-bearing formation. That the infiltration is of relatively recent date in one particular instance is shown by the presence of chert veins in an acid porphyry which cuts the jasper and the greenstone north of Mud Creek Bay. Had iron been present in this siliceous solution jasper with small masses of ore instead of the veins of chert might very well have been formed.

RELATIONS OF SOUDAN FORMATION TO ADJACENT FORMATIONS.

RELATIONS TO THE ELY GREENSTONES.

From a scientific point of view one of the most interesting problems confronted in the study of the Vermilion district is that of the relation of the iron formation to the Ely greenstones. From an economic standpoint this is also one of the most important problems. It was likewise most puzzling and most difficult. It is believed that the relations between the greenstones and iron-bearing rocks have now been determined.

In approaching the question we must bear in mind the fact that this iron-bearing formation was probably at one time spread over nearly the entire district with more or less uniformity. Ever since that time, however, it has been subjected to mountain-making forces and active processes of erosion. The few areas of this formation which we now find are only those remnants of it which, being infolded in the underlying formation and thereby to a certain extent protected from erosion, have fortunately remained.

It has already been stated that most commonly the contacts between the greenstone and the iron formation are wanting. Still a sufficient number of good contacts were found to leave no doubt whatever as to the usual relation. Where not wanting the contact is usually exposed only over a very small area; where favorable exposures have been found the usual relations are such as are described in the following paragraphs.

The jasper of the iron formation occurs in the greenstone in lenses of varying size, ranging from 6 inches in width upward, the smaller ones being very common. The larger ones are rarely exposed over their entire surfaces, and such partial exposures make it very difficult to trace the various bands through the full length of the lenses, and it is practically impossible to recognize the same bands at different places unless one can trace them over the intervening areas. About a quarter of a mile north of the north shore of Fall Lake, in the NE. $\frac{1}{4}$ of sec. 13, T. 63 N., R. 12 W., the jasper is found in the greenstone in narrow bands, from 4 to 5 inches wide, which are bent sharply upon themselves, showing the extreme folding to which they have been subjected. Similar bands varying in width from a few inches to 2 feet are found in the NE. $\frac{1}{4}$ of sec. 7, T. 63 N., R. 11 W., infolded in the amygdaloidal ellipsoidal greenstones, and there form small synclines pitching east. South of Moose Lake, in sec. 4, T. 63 N., R. 9 W., on the narrow neck of land separating the two small lakes, the infolding of the jasper in the greenstone is well shown. In many excellent exposures it is clear that the jasper overlies the greenstone. One especially good exposure showing this relation very clearly can be seen on the north side of Jasper Lake. Here the iron-bearing formation is in Canadian territory, but is in direct continuation of and really in connection with the

Vermilion range of Minnesota. At this place the jasper stands with a dip of about 85° west, with the greenstone both to the east and to the west of it. One might be inclined to say, and with good reason from this part of the exposure, that the jasper is included in or interbanded with the greenstone. However, as we go over the end of the exposure, coming south down the hill along the strike, it can be seen that this relation is due to the exceedingly close infolding. The jasper is closely compressed and lies in a syncline of greenstone, and in the inclined section through the jasper and greenstone displayed on the hill slope, the greenstone can be seen to pass down under the jasper, from both the east and the west sides. Indeed, at one place a subordinate anticline of greenstone was observed projecting up through the jasper, the jasper wrapping around it and dipping away from it. On Otter Track Lake essentially the same relations can be seen to exist. Actual contact between the iron-bearing formation and the greenstone was observed, but no fragmental material occurred between them. Clearly, however, the jasper overlies the greenstone, having been deposited upon this as a basement, for the bands run parallel with the contours of the greenstone mass. In this particular instance the exposures are not quite so good as those upon Jasper Lake, but are still good enough to enable one to determine the relations with certainty. On Emerald and Big Rock lakes, both of which lie in Canadian territory, north of Knife Lake, there are several exposures of jasper in intimate association with the greenstone. All the jaspers of Emerald Lake, especially, are beautifully and curiously folded. This folding is particularly well seen on the western edge of the large island about a mile and a half west of the end of the lake. As one rows along the shore he may see most intricately folded jasper bands which closely resemble the jaspers on Otter Track Lake figured by H. V. Winchell in the Minnesota reports. There are fan-shaped folds and curious interlockings which would be almost incredible if not seen. The jasper, although so rigid, has evidently obeyed the law of flowage by filling up every chink and corner throughout the mass. It is still somewhat questionable how far this formation may have been folded before it was jasperized. At this ledge upon the island the broad jasper bands were seen to be bent around in a curve having a radius of from 2 to 4 inches, sections across them giving a roundish surface, making them appear almost like a series of closely laid pipes.

In the cases mentioned the iron-bearing formation was found in immediate contact with the greenstone at a great number of places. In all cases the contact is sharp. There is no gradation from the greenstone through a distinctly clastic transitional rock into the iron-bearing formation. The field relations described are evidently such as could be produced only by the closest infolding of a superimposed rock in the rock below it. This intricate infolding is furthermore shown by the contorted character of the banded iron formation.

The iron formation is not confined to the normal relatively unmetamorphosed greenstones, but is also found in those which have been metamorphosed by contact with the granite into the amphibole- and mica-gneisses, as in the occurrence in the SE. $\frac{1}{4}$ of sec. 32, T. 62 N., R. 13 W., south of Burntside Lake. In passing, it may be mentioned that the presence of the iron formation in these amphibole-schists and gneisses is further proof of the correctness of the statement already made that these are but much metamorphosed greenstones, and essentially the same, at least so far as their original condition is concerned, as the greenstones which are not very far distant.

Reference has been made to the fact that the jasper at the contact with the greenstone is sometimes brecciated. One especially clear case of this is the occurrence on the south side of the North Lee pit. Here the jasper fragments derived from the iron-bearing formation are, especially near the greenstone. more or less completely surrounded by a matrix of the adjacent greenstone, which evidently, under the pressure exerted upon it, became more readily plastic than did the more brittle jasper. Commonly brecciation does not occur at the contact. The greenstone is usually schistose along such contacts. This is illustrated 220 paces north of the southeast corner of sec. 15, T. 62 N., R. 13 W. Here there is a bare roche moutonnée, which consists for the most part of the very dense massive greenstone. At one place there was found a belt of schistose greenstone about 3 feet wide lying immediately next to the massive form above mentioned. In this schistose greenstone there are two narrow bands of east-west striking jasper, each about 4 inches in width. These were separated from each other and from the massive greenstone by the schistose form of the greenstone, which to the south as well as to the north grades into the massive variety. It is hardly possible to interpret this occurrence as anything else than a case of infolding. As the result of the accompanying movement, the greenstone was rendered schistose immediately adjacent to the jasper and nearest to the plane between the rocks of diverse character along which the greatest movement naturally took place, this schistosity diminishing in degree away from the plane of greatest movement.

In several places in the district careful search made expressly therefor has disclosed the greenstone with a conglomerate lying on it and consisting of material derived from the greenstone. The conglomerate is followed by finer-grained clastic sediments of essentially the same character as the conglomerate itself, and these sediments are in turn succeeded by the iron formation proper, consisting of the normal cherts, jasper, and iron oxide in alternate bands. Occasionally a clastic band occurs with the iron formation proper. Such definite relationships were observed at several places, as in sec. 10, north of Armstrong Lake. Here the greenstone is overlain by a conglomerate derived from it, which is succeeded to the north by the iron formation, which contains a large quantity of iron pyrites. The greenstone also contains large quantities of the iron pyrites scattered through it in crystals which have to a great extent been changed to limonite. Another locality is north of Robinsons Lake, just south of the north quarter post of sec 7, T. 62 N., R. 13 W. A number of other places were found in which, however, the relations were not quite so clear, the complete sequence being interrupted by lack of exposures; they are therefore not referred to specifically. The above-mentioned relations show clearly that the main part of the iron formation rests upon the greenstone as a basement, and consequently is younger than the greenstone.

But is all of the iron formation younger than all of the greenstones of the Vermilion area? Apparently not, but there is occasionally an interbedding of the iron formation with some of the greenstone. The evidence for this is found in the distribution of the iron formation in long belts separated from one another by areas of varying width underlain by the greenstones. These belts have been traced for various distances, in one case for a distance of 16 miles. In no case is the iron-bearing formation continuously exposed over such extent, but the exposures are, nevertheless, so numerous as to show conclusively that the intervening areas without exposures are underlain by the iron-bearing rocks. Associated with the iron-formation rocks of these belts there is more or less greenstone. This is frequently found in contact with the iron-bearing rocks and tends to separate the formation into a number of small belts whose continuity can not be traced on account of the rarity of exposures. The greenstones which occur in this iron-formation belt are of different kinds, and it is supposed that they may represent flows of greenstone geologically contemporaneous with rocks of the iron formation. The exposures are so isolated, however, that it is not feasible to connect them and separate the rocks into individual flows or sills. Furthermore, it is in these belts of the iron-bearing rocks that the above-mentioned clastic rocks derived from the greenstones and underlying conformably the iron-bearing formation have been found. In view of these facts, we are led to believe that some of the rocks of the iron-bearing formation, while resting upon the basement of greenstones, are likewise overlain by greenstones, or, in other words, that some of the iron formation is interbedded with greenstones which are of volcanic origin.

Thus the clastic sedimentary deposits derived from and overlying the lava flows may grade up into nonclastic sediments. The conditions of sedimentation vary from place to place in the area, hence we get a gradual change from mechanical sediments to organic sediments (cherty ferruginous carbonates). Where the conditions were not favorable for the formation of the clastic sediments the nonclastic sediments were deposited without the conglomerates and graywackes intervening between them and their igneous rock basement. Hence we now find them resting upon the greenstones with a sharp line of demarcation between them, or at most with a narrow zone of schistose greenstone intervening. These sediments were in their turn in some cases buried by lava flows, which again at a later date were covered by succeeding sedimentary deposits. These processes continued throughout a shorter or longer period. It is due to this fact that such intimate relationship exists between the greenstones and the associated—in the main younger—iron-bearing formation. As a result of this intimate relationship it has been impossible to logically separate the two in a more marked way than has been done in the above pages. While of a distinct method of origin, their formation took place within essentially the same period of time. In general, however, it is possible to recognize the greenstone as the true basement rock of the district, correlative with the Archean rocks of the other Lake Superior iron-bearing districts.

Within the greenstone are areas of jasper of very irregular shape and size which do not possess the regular banding seen in the jasper of the large areas of the iron formation. Such small areas of jasper are not uncommon in the northern half of sec. 21, T. 62 N., R. 14 W., from 1,150 to 1,260 paces north, 950 paces west of the southeast corner; again, in secs. 1, 2, and 3, T. 61 N., R. 15 W. These jasper areas are of irregular shape and appear to owe their origin to a process of infiltration similar to that which forms veins. This is clearly the mode of origin of these irregular masses of jasper which occur in the midst of the ellipsoidal greenstones, filling the angular interstices between the ellipsoids (see page 139). Some of these irregular masses may be remnants of the iron-bearing formation deposited in irregularities of the underlying rocks, but this mode of origin could not be proved for any occurrence. There is a further possibility that some of these masses may be inclusions of the iron formation in the eruptive greenstones. This explanation has been offered by H. V. Winchell and others for a large part of the iron formation of this district and has been cited as proof that the iron formation was older than the greenstones. However, as already shown, the presence of the conglomerates clearly disproves this age relationship for the greater part at least of the iron formation. Infolding may as readily explain the intimate character of the relationship between the greenstone and the iron formation as the suggested intrusive relationship. For instance, when we find small isolated lenses of the iron formation lying in the greenstone, with the surface only exposed, or when, as not uncommonly happens, narrow bands of the formation are bounded on two sides by the greenstone, their lateral extension being concealed in the other two directions, the exposures are too imperfect to enable one to determine the exact relation of each mass of the iron-bearing formation to the greenstone. Nevertheless, when considered in connection with other instances, such as have been mentioned and described, where the relations of the large masses of iron formation to the greenstone are clearly those due to infolding, it will be readily admitted that the relations of the other doubtful cases are also best explained as due to this same thing. Especially are we inclined to this conclusion when the close folding to which the rocks of the district have been subjected is fully recognized. Admittedly some of the greenstones may be younger than some of the iron formation; for instance, the sills and dikes forced into the iron-bearing belts toward the close of the period of volcanic activity, or some old flows which have poured out from the land into the adjacent sea while the iron-bearing formation was being deposited. In no case, however, has a jasper mass been found which could be conclusively shown to be included in the greenstone as a result of igneous intrusion.

RÉSUMÉ OF RELATIONS TO ELY GREENSTONES.

In view of the above-described modes of occurrence of the iron formation in association with the greenstone, we reach the following conclusions concerning the age relations of the two: A portion of the iron formation—and this appears to form by far the predominant part of it—is clearly younger than the greenstone; for instance, those masses of the formation that overlie the clastic sediments which have plainly been derived from the underlying greenstone. Other very subordinate portions of the formation are interbedded with the greenstone, and hence are partly contemporaneous with it. This is shown in those cases where there is greenstone overlying the iron formation. Moreover, it is not improbable, although not susceptible of definite proof, that some of the smaller areas of the iron formation are included in a greenstone which has been later intruded through the iron formation. Lastly, small areas of jasper, chert, and ore, similar in general characters to the iron-bearing rocks, are secondary infiltration products.

In order to get a clear understanding of the conditions which would permit such a variety of relationships between the greenstones and the iron formation, it is necessary that we call to mind the conditions under which these two formations originated. A study of the greenstones has led to the conclusion that they were formed by volcanic outbursts. Just as at the present day we have lavas and tuff masses outpoured upon the land and partly occupying adjacent water areas, sedimentary deposits being formed offshore where the conditions are favorable for them, just so did we have similar conditions in the early history of the Vermilion district. As a consequence of this volcanic outburst on the land and the simultaneous formation of sedimentary deposits in the sea, we now find the two intermingled. In this way we can conceive that clastic sedimentary deposits might be derived from and overlie lava flows, and grade up into nonclastic sediments. Where conditions were not favorable for the formation of clastic sediments, nonclastic sediments were formed without the conglomerates, etc., intervening between them and their igneous-rock basement; hence we now find them resting upon the greenstones with a sharp line of demarcation between them. Conditions of sedimentation varied; hence we get a gradual change from mechanical sediments to organic sediments (iron-bearing rocks). The sediments in their turn were buried by lava flows, which again at a later date were covered up by succeeding sedimentary deposits, and so on. So far as we can ascertain, volcanic activity continued only during the time when the lowest sediments were being formed. We have no evidence that volcanic activity continued during that later period in which the iron-bearing sediments were deposited. Lastly, through this series of sediments and lavas intrusive masses would be forced, which would, in some places at least, include portions of the sedimentary deposits as well as of the lava associated with them.

RELATIONS TO THE ARCHEAN ACID INTRUSIVES.

On Soudan Hill and elsewhere the iron-bearing formation is intruded by acid intrusives belonging to the Archean eruptive series. At the Eaton explorations at the SE. ¼ of sec. 7 and SW. ¼ of sec. 8, T. 62 N., R. 14 W., the jasper and ore are cut by granite-porphyry, which carries very large quartz phenocrysts. Also north of Mud Creek Bay, in the SE. ¼ of sec. 1, T. 62 N., R. 15 W., the jasper is both cut by and included in a granitic eruptive. On the north shore of the lake, in sec. 18, T. 62 N., R. 12 W., the jasper is cut by granite-porphyry. Granite dikes cut the iron-formation belt south of Ely in secs. 3 and 4, T. 62 N., R. 12 W. The jasper belt extending through the south half of sec. 10, T. 63 N., R. 10 W., is also cut by dikes of granite and granite-porphyry. Similar occurrences could be multiplied, all showing the iron-bearing formation cut by the younger acid eruptives, but it is not necessary to further emphasize this relationship, which is indisputably clear.

RELATIONS TO OVERLYING SEDIMENTS.

The iron formation is in places overlain by a series of sediments of clastic origin. Where contacts between these series were observed it was found that the relationship existing was that of two unconformable sedimentary deposits. The proof of this is in the fact that the upper, younger sedimentary series contains in it fragments of the underlying, older series, the iron formation. The details concerning the relations of these two formations are given under the discussion of the later sediments.

RELATIONS TO BASIC ERUPTIVES.

In several places the iron-bearing formation is found to have been cut by basic eruptives. Thus, for example, in sec. 27, T. 62 N., R. 15 W., the jasper is cut by dikes of greenstone which must be younger than the jasper, and very probably belong with the Lower Huronian basic intrusives. Again, south of Ely, in secs. 3 and 4, T. 62 N., R. 12 W., basic intrusives are found to cut across the iron formation.

AGE.

From the preceding paragraphs it will have been learned that the Soudan formation is in general younger than the Ely greenstone, the oldest rock of the district, but on the whole so intimately associated with it that the two must be considered as belonging to the same great period of the earth's history, the Archean.

THICKNESS.

It is impossible to make any reliable estimate of the thickness of the iron formation, and this for many reasons. In the first place, the exposures of the formation are so isolated and the formation itself throughout is of such uniform character that it is impossible to recognize the same horizons in it in different parts of the district. No definite basement has been found from which to begin an estimate of the thickness. The very close folding to which the rocks of the district have been subjected adds to the complications. The thickness of the Soudan formation, as inferred from its surficial extent rather than from any definite measurements, is presumed to reach several hundred feet.

INTERESTING LOCALITIES.

On the bare hills just north of the northernmost houses of the town of Tower there are a number of exposures that show the relations between the iron formation and the associated rocks. For instance, the southernmost exposures on these hills are conglomerates made up of pebbles of jasper, slate, and chert. These materials have been derived from the iron-formation rocks which immediately underlie them, and in places are seen in juxtaposition with the conglomerate. Erosion has removed the conglomerate in some cases, leaving small areas of the jasper only a few yards in extent surrounded by the conglomerate. Associated with the jasper at this place are very narrow bands of black graphitic slate. It is from some of these bands that the fragments of slate in the overlying conglomerate have been derived. There is an area about 100 yards wide on the slope of this hill in which the conglomerate and underlying jasper are intimately associated. North of these exposures occur the iron-formation rocks, consisting of jasper, cherts, and iron ore interbanded and closely infolded with the green schists. The iron formation has its normal characters, which have already been described. The green schist associated with it possesses an exceedingly well-developed fissility, which strikes N. 70° E. The schist is much crumpled in places and shows minor faulting, with bending of the lines of schistosity. The faults cut across the schistosity at an angle of 45° and extend about northwest-southeast. This schist is impregnated in areas of irregular outline with iron, especially along the southern side of the exposures nearest the jasper. A great deal of vein quartz has also been infiltrated into the schist and is found in thin sheets marking the planes of schistosity, and also in fine systems of rectangular veins which cut the schistosity. The green schist and iron formation are most intimately infolded, forming a series of anticlines and synclines having very steep pitches. The axes of the folds have a strike approximately coinciding with the strike of the schistosity in the green schists, N. 70° E., showing an exceedingly close folding of the rocks. A great number of these small folds was observed, and in some cases the bands of iron formation or of schist could be traced through several folds. It is very clear that the close infolding here has produced a kind of fluted structure which is best developed on the saddle connecting Tower and Lee hills, which stand en échelon to each other from northwest to southeast.

The same kinds of intricate plications of jasper and green schist can be seen on the numerous exposures on Soudan Hill. An especially good one occurs on the north flank of the hill about 1,040 paces north, 330 paces west of the southeast corner of sec. 28, T. 62 N., R. 15 W. Numerous other cases may be observed west of the Montana pit and on the north flank of the hill north of No. 8 shaft. Several good exposures occur also along the road leading from the top of the hill to the compressor, and also near the top of the hill on the right side of the tramway leading to the compressor.

On the south shore of Vermilion Lake in the SE. ¼ of sec. 20, T. 62 N., R. 15 W. on the point between Swede Bay and Vermilion Lake there are a number of exposures of the iron formation in close association with the later sedimentaries. Indenting the northeast shore of this point there is a small bay, on the west shore of which (almost due west of a small reef of conglomerate) there is an exposure of jasper. This jasper exposure is only about 75 paces across and is extremely plicated, showing a number of distinct anticlines and synclines with axes striking east and west and plunging east at the high angle of 80°. On this exposure there are also some beautiful examples of friction breccias on a small scale. Following this exposure inland we pass over several other jasper exposures showing nothing of especial interest, so far as the iron formation itself is concerned, but lying above the iron formation here and there we find a patch of conglomerate derived from it and showing distinctly its relationship to the underlying jaspers. About halfway across the point we reach a place where a considerable area of the jasper is exposed. At this point the jasper is extremely plicated, like that upon the shore. The axes of the plications strike about N. 75° E. and form an arc of an oval whose long axis trends N. 75° E. It seems very clear that we are at this place just east of or near the apex of a small east-west anticline. A conglomerate lies around the jasper, bordering it, with an occasional patch still remaining on the top, and hence lying in the midst of the jasper area. The conglomerate has its greatest development to the north, while to the south the slates are most common.

Good exposures near the North Lee pit on Lee Hill, northeast of Tower, offer excellent opportunities for a study of the relations between the green schist and the jaspers. A green chloritic schist is exposed in a practically solid mass for about 125 paces to the south, then follows the jasper, and again, north of the jasper, comes the solid greenstone for something like 75 paces, where an alternation of jasper and green schists begins, eventually followed, still farther north, by a large mass of greenstone. The schistosity in the schists strikes east and west. Nearest the main mass of the jasper the schist contains a few small lenses and stringers of jasper and chert, which extend along the planes of schistosity and clearly have been introduced into the rock since it was rendered schistose. The surface exposures of the schist east of the jasper are disconnected, but it is reported by the mine captain who had charge of the North Lee pit, now filled with water, that underground the jasper is cut off by the greenstone which surrounds it to the east. The jasper exposed, especially to the west of the North Lee pit, is very badly fractured, and ore has been introduced since the fracturing, healing the cracks and filling the cavities. Moreover, along the edge of the pit from which the ore body has been removed there can be seen remnants of banded lean ore. These bands are continuous with the bands in the jasper lying next to and continuous with the ore. There is here a gradation from a small mass of rich ore through a very hematitic jasper into the normal jasper. The fracturing and brecciation of the jasper are indicative of the extreme folding to which it has been subjected. This is further shown by the presence of a fairly extensive breccia along the contact between the southern wall of green schist and the jasper. Along this contact has occurred brecciation of the chert and jasper, and angular to subangular fragments of these form the pebbles for the most part, with the green schist occurring chiefly as the matrix. Occasionally a fragment of the green schist occurs, also as a pebble, in the matrix. Since the formation of the breccia, iron has been infiltrated into it, and this has tended in many places to cement it together, so that at some localities it contains very nearly enough hematite to be considered a lean ore. In places along this contact a great deal of white quartz has been infiltrated, showing that water has been very active here.

In the SW. $\frac{1}{4}$ of the NW. $\frac{1}{4}$ of sec. 3, T. 61 N., R. 15 W., there are a number of exposures of jasper which show extreme plication and infolding of jasper and green schist. Here also there is a band of breccia consisting of fragments of jasper and chert in a green schist matrix. Similar breccias have been observed also at other places throughout the district. The jasper upon these exposures is for the most part that which is usually called the black or hungry jasper. It is a magnetitic chert. This in places shows a fine banding, probably sedimentary banding. In the NE. $\frac{1}{4}$ of the SE. $\frac{1}{4}$ of sec. 1, T. 61 N., R. 15 W., there is an occurrence of jasper which has been explored by means of test pits and diamond drill. The jasper belt here has a width of from 15 to 30 feet, strikes N. 70° W., and dips 90°. It is exposed for a distance of about 100 paces in an east-west direction. South of the jasper there is massive greenstone. On the north side of the jasper there is a greenstone which has ellipsoidal parting and in places appears tuffaceous. No good sedimentary banding is shown, however. Here, it seems, there was an interbanding of the iron formation with the greenstones, it having been covered up, perhaps, by a flow of lava represented by the ellipsoidal and tuffaceous rock. In the SE. ¼ of the SE. ¼ of sec. 7, T. 62 N., R. 14 W., on what is known as the Eaton property, there is a large exposure of much plicated iron formation which in one place near the shaft has been cut through by dikes of granite-porphyry containing large phenocrysts of quartz. The intrusive relationship of this porphyry to the jasper can be well seen here. The jasper occupies prominent hills in the midst of an area containing heavy drift deposits which conceal the greater portion of it, but numerous exposures of greenstone north and northwest of the jasper areas indicate that the greenstone at least partially surrounded the iron formation, and, as shown by relations of these rocks elsewhere, underlies the jasper. Just west of the shaft, about 300 paces distant, is a bare knob of greenstone cut through by a dike of granite-porphyry which is believed to be a continuation of that cutting the jasper near the shaft. On this bare knob there were observed in some places structures which looked fragmental, making the rock appear as though it were partially a greenstone tuff or a brecciated greenstone. It could not be determined whether this fragmental portion of the greenstone was a volcanic tuff or a basal conglomerate lying upon the greenstone and below the iron formation.

About one-fourth of a mile north of the southeast corner of sec. 1, T. 62 N., R. 15 W., there are a number of fairly good exposures of the iron formation. This is here very intimately associated with greenstone, with which it is clearly infolded, both the jasper and the greenstone there being cut by acid dikes. The belt in which this iron-formation material occurs was traced to the north of east by means of a number of discontinuous exposures for about 2½ miles. There is a large exposure just north of the little lake on the section line, between secs. 5 and 6, T. 62 N., R. 14 W. It is very much contorted, and represents a southwestward-plunging anticline. Mining has been done at this point to a slight extent, some ore having been brought to the surface, although none has been shipped.

A number of explorations farther east along the same belt of rock have likewise disclosed the presence of the iron formation, but thus far only very small quantities of ore have been found.

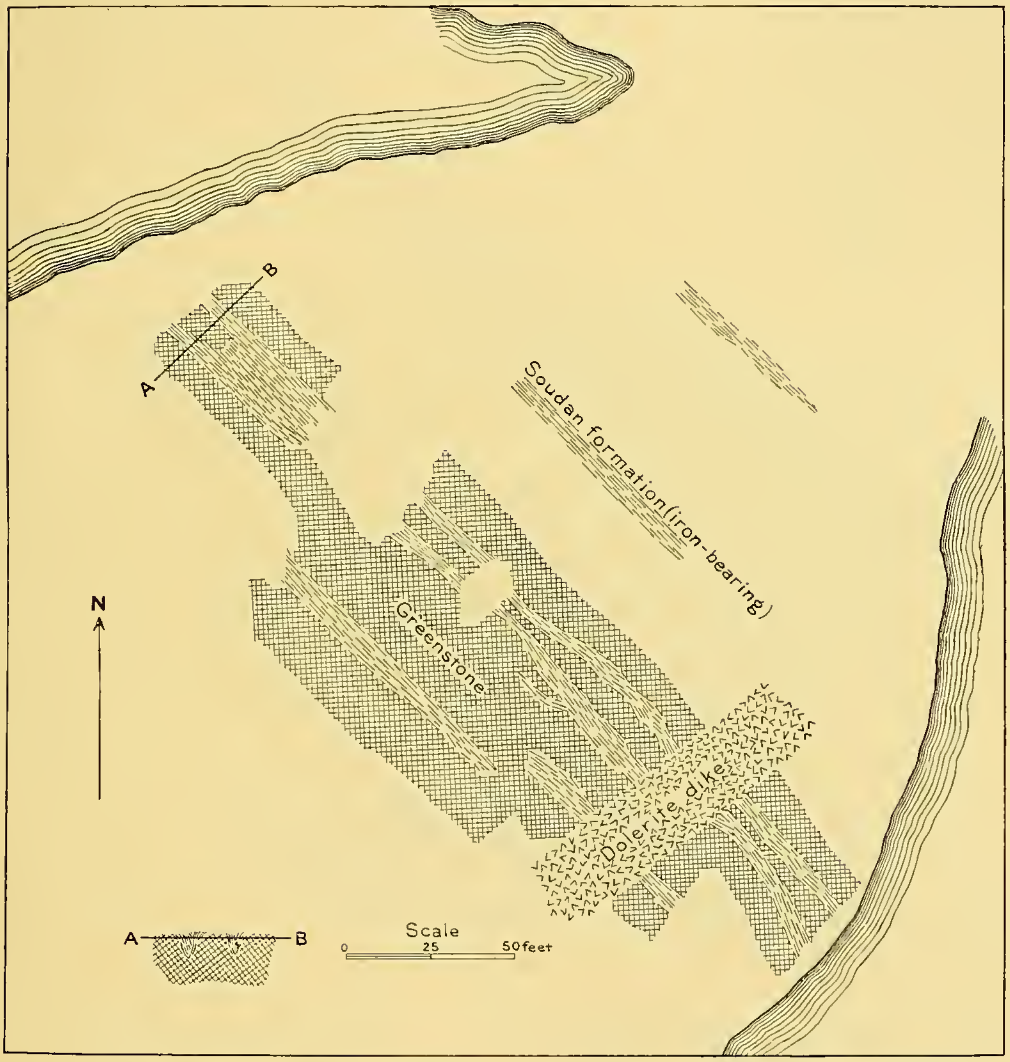


Fig. 3.—Sketch showing Soudan formation infolded in Ely greenstone, both cut by Keweenawan dolerite dike.

South of Moose Lake small stringers of jasper have been observed at a number of places, associated with the Ely greenstones, which are there well exposed on the bare hills. On the narrow strip of land in the NW. $\frac{1}{4}$ of sec. 4, T. 63 N., R. 9 W., separating two small lakes, there are exposed several narrow belts of iron formation intimately associated with the greenstone. Five distinct bands of iron-formation material were observed, each only a few paces in width, and in the belts farthest south the exposures were sufficiently good to show very well the intimate relations of the greenstone and the iron formation. The iron formation is very

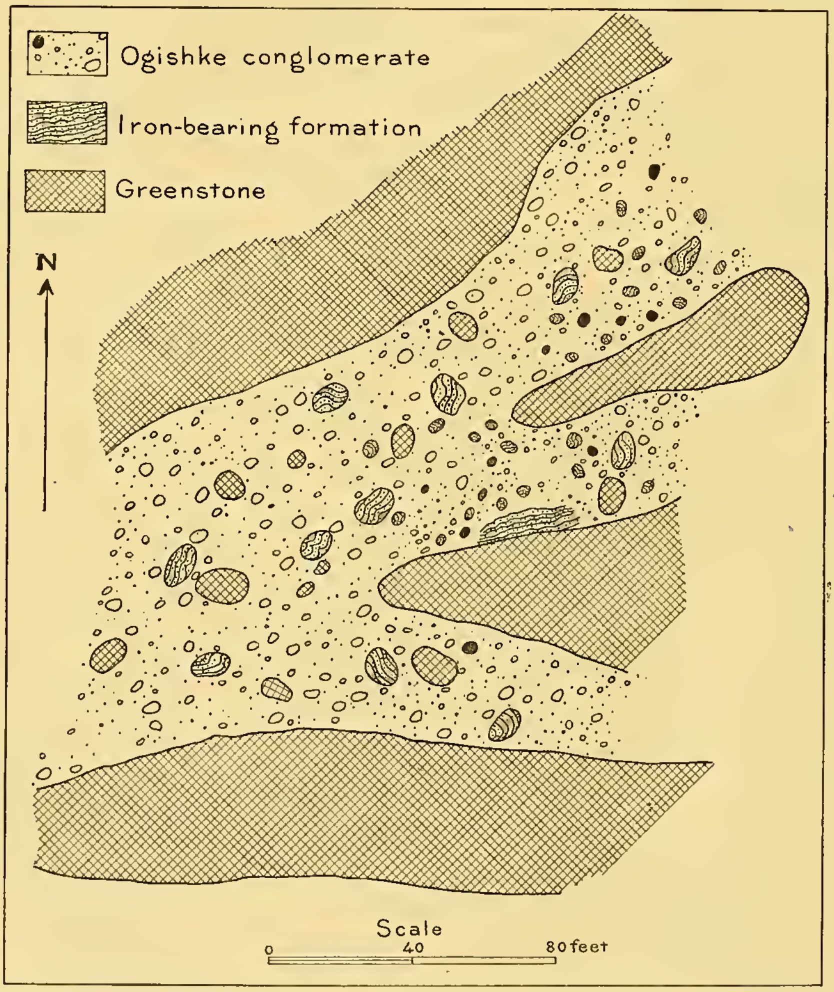


Fig. 4.—Illustration showing distribution and relations of Ely greenstone, Soudan formation, and Ogishke conglomerate at a place south of Moose Lake.

clearly infolded in the greenstone, and subsequent truncation of these two formations has resulted in producing very intricate surface relationships. At one place a broad dike of dolerite has cut across both the preexisting formations, and, indeed, it was traced for about half a mile across the country. Fig. 3 illustrates the relations observed at this place. About one-fourth of a mile due north of this locality, in sec. 33, T. 64 N., R. 9 W., there are some exposures showing very clearly the relations which exist between the greenstones, the iron-bearing formation, and the sediments that occur in such large quantities in this area south of Moose Lake. At this place the greenstones occupy the opposite sides of a considerable depression in which occur most commonly the exposures of the fragmentals. Occasionally an irregular area of the old ellipsoidally parted greenstone rises through these fragmental deposits (fig. 4). At the place mentioned, a narrow belt of iron formation, about 20 feet in length, was observed lying on the north side of such a small irregular area of greenstone. South of this there were small, irregular areas of iron formation completely surrounded by the greenstone. Immediately adjacent to the iron formation and the greenstone occurs the Ogishke conglomerate, consisting of fragments of greenstone with, in the immediate vicinity of the jasper, considerable numbers of fragments of jasper, showing very clearly that it is derived from the jasper and the greenstone, which are the underlying formations. Fig. 5 is a sketch illustrating the association of the rocks at this locality. It is very evident that the irregular distribution of the greenstone is due to the intricate folding to which all of the rocks have been exposed, and the subsequent truncation of the folds, which has left the outcrops of the formations in their present relations.

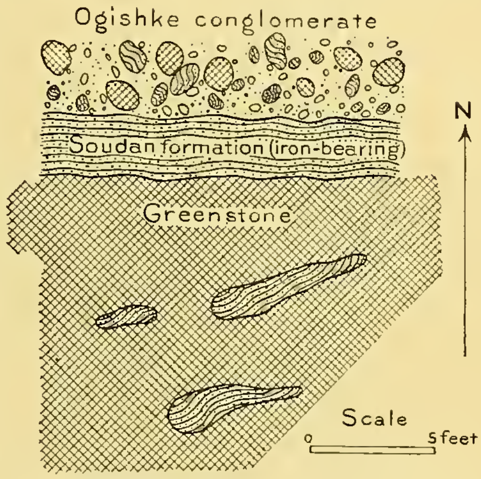


Fig. 5.—Sketch showing association and relations of Ely greenstone, Soudan formation, and Ogishke conglomerate.

On the Canadian shore of Otter Track Lake, on the west side of the strait leading to the north and south arms, and just beyond the main portion of the lake, there is a considerable exposure of iron formation in contact with the old greenstones. The formations are well exposed along the lake shore, being present in cliffs which are about 75 feet high and very nearly perpendicular. The contact between the jasper and the greenstone is very irregular on a large scale, although when examined in detail the line is usually pretty sharp. The actual contact between the two was closely studied to find whether or not a zone of clastic rocks intervened between them, but such a zone was not found, the contact being very sharp. The greenstone, it is true, is somewhat schistose along the contact, but this may

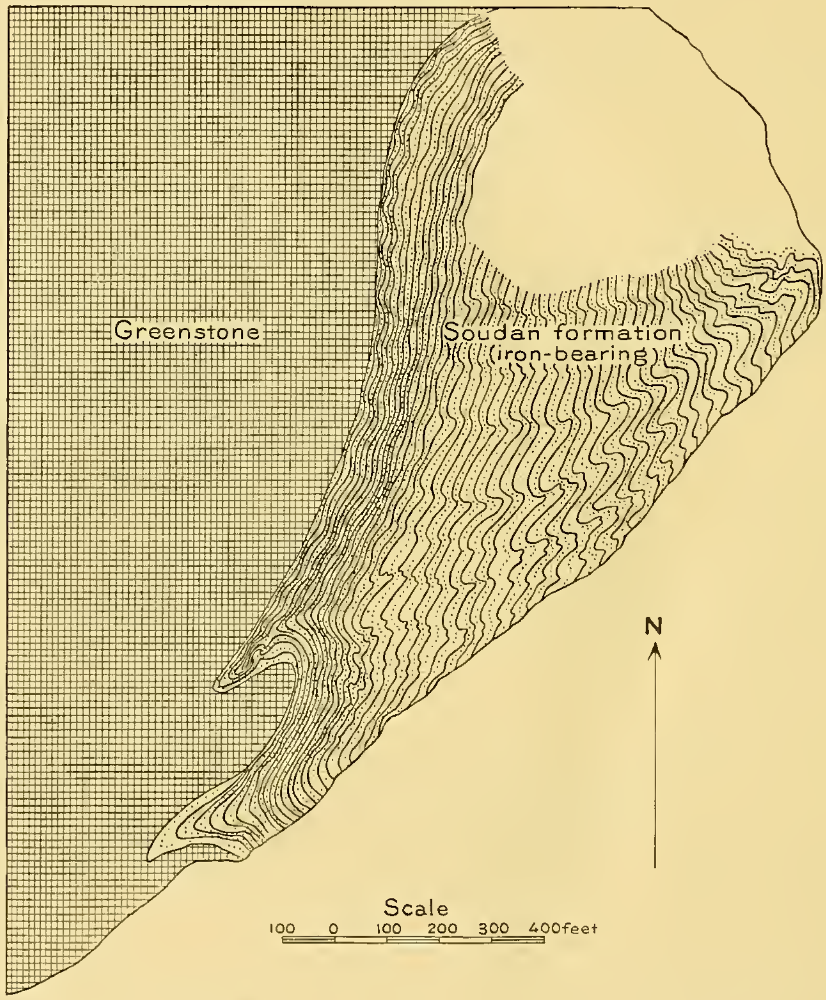


FIG. 6.—Sketch showing relations between Soudan formation and Ely greenstone on Otter Track Lake.

be due to the movement that has taken place between the two formations as a result of the folding. Fig. 6 is a sketch showing the occurrence of these rocks at Otter Track Lake.

The regular canoe route was followed northward from Otter Track Lake to Jasper Lake, and on the north shore of Jasper Lake, west of the bay from which the portage leads northward from the lake, exposures of iron formation were found and carefully studied. Here, again, special

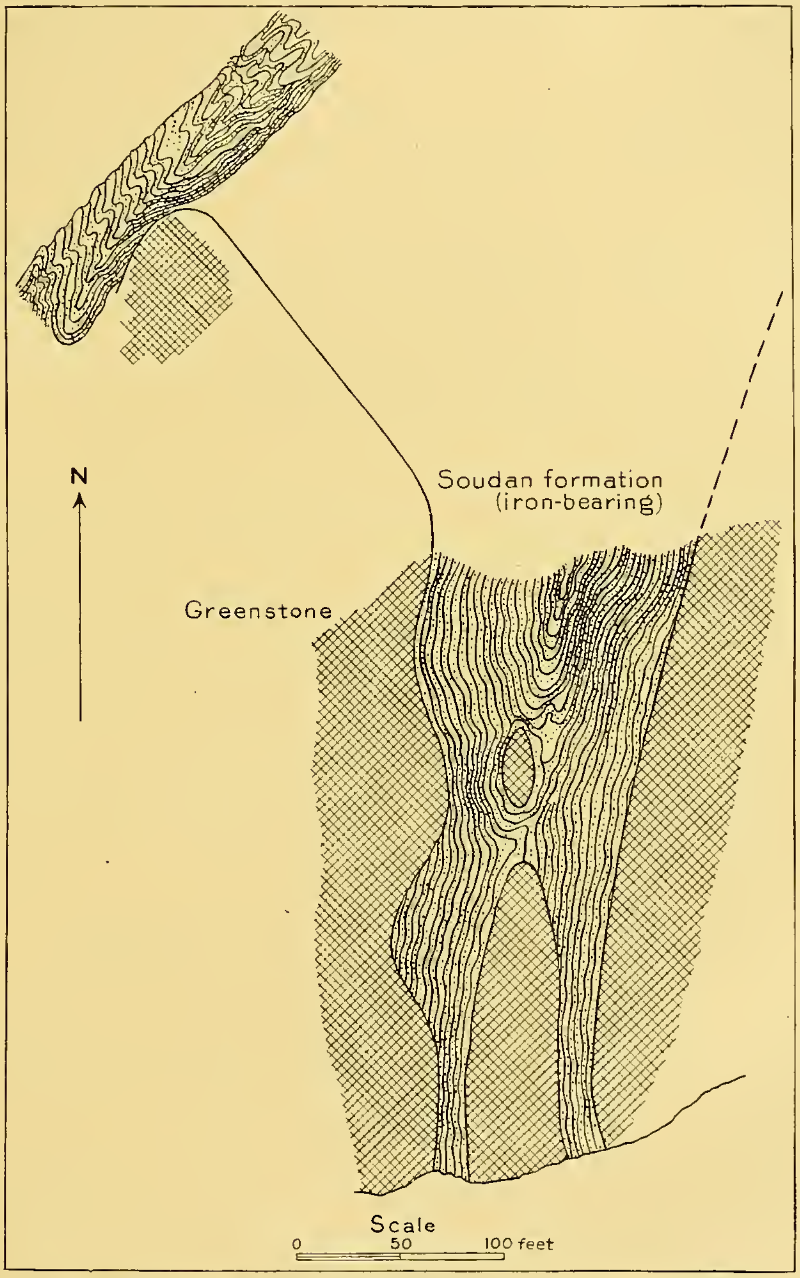


Fig. 7.—Sketch showing relations of Soudan formation and Ely greenstone on Jasper Lake.

attention was paid to the contact between the iron formation and the greenstone, but very careful search showed no indication of any clastic material between them. Nearly everywhere this greenstone is perfectly massive; in a few places it shows a slight schistosity parallel to the contact, probably the result of the shearing caused by the close folding. The iron formation is closely infolded in the syncline in the greenstone. The broadest part of the syncline—that is, the place where the jasper has its greatest width—is at the top of the hill. From this point down to the lake shore the descent is at a rather sharp angle, and the fold has here been beveled off. As a result of this beveling a subordinate anticline is first brought to the surface as an oval area near the center of the main syncline, and as we come still farther south the deeper truncation of the fold has separated the main syncline into two subordinate synclines occurring in very narrow belts separated by the intermediate greenstone area, as shown in fig. 7, from a sketch made in the field.

On the portage between Big Rock Lake and Emerald Lake, north of the international boundary, a mass of iron formation was seen which was estimated to be about 100 feet across, north and south. Its contact with the greenstone south of the trail was found, and is here knife-like in its sharpness, there being absolutely no clastic material between the greenstone and the jasper. The jasper is much broken, has very fine jointing, and the brilliant red variety makes up the greater portion of the formation. Some of the bands of the bright-red jasper are 6 inches across. Bands of white chert are infrequent, although present, and the iron ore in narrow bands makes up the remainder of the formation.

INTRICATE FOLDING OF SOUDAN FORMATION.

The intricate folding of the iron formation can be well seen at a number of places just north of the international boundary; for example, on Emerald Lake, where it is most beautifully and curiously folded. On the west side of the largest island, which is about in the center of the lake, bands of the jasper are bent into fan-shaped folds and curious interlockings, a description of which would be almost incredible. The jasper, although so rigid, has evidently obeyed the law of flowage in filling up every chink and corner throughout the complexly deformed mass. How far these rocks were folded before complete jasperization took place is questionable. At this ledge the broad jasper bands turn around and form an elbow, having a radius of from 2 to 4 inches, giving a roundish surface on top, looking like cross sections through a set of closely laid pipes. The minor folds at this exposure pitch to the west at angles varying greatly, but ranging mostly between 50° and 30°.

The intricate infolding of the green schists and jaspers may be observed at numerous places on Lee and Tower hills, just north of the town of Tower. A study of these will impress one with the extraordinary complexity of this folding. Not only are the dips substantially vertical, but the pitches of the folds are vertical, or nearly so. The result of this is that where the green schist and the jasper come together the contact is most extraordinarily complex. It runs in and out, and in places the jasper might be supposed to be over the green schist; in other places the reverse seems to be the case; and in still other instances one is strongly inclined to believe that one of them cuts the other as an intrusive. In some places there is brecciation along the contact, so that between the green schist and jasper there is an intervening zone of pseudo-conglomerates. One of these conglomerates has a green schist matrix in which are bedded numerous fragments of banded jasper. Some fragments are well rounded, others subangular, others have curious points, and a considerable number are in roughly rhomboidal form (Pl. VI, *C*). The schistosity extends roughly east and west. It cuts the schist, but usually stops abruptly at the jasper bands. This adds still another feature to the complexity of the structure at the contacts. However, although one may be confused by examining the details of some of these exposures, if one follows the broad distribution, he will find in many places that the schist and jasper occur in belts which can be separated as such, the major folds being made out in many cases.

One of the largest exposures of jasper in the Vermilion district is that which forms the prominent peak known very commonly as Jasper Peak, although the name Chester Peak has prior claim. The jasper is exposed over almost the entire area of the hill. The outcrops, while not solid, are nevertheless so numerous as to enable one to determine very easily the structural features. The south side of the hill is nearly vertical, and gives very good sections through the intricately folded iron formation. A study of the hill shows that the iron formation is folded into a great synclinorium made up of a number of closely folded synclines and anticlines. The general strike of the axis of the synclinorium is N. 60° E., and the axis plunges to the east, though the exact angle is not known.

There are some large exposures of jasper in the NE. $\frac{1}{4}$ of sec. 25, T. 63 N., R. 12 W., and this locality has been prospected thoroughly by means of diamond-drill borings. The way in which the iron-bearing formation is closely infolded in the Ely greenstone is well shown upon Sheet XXVI of the accompanying atlas, the data for the construction of which have been obtained from the Minnesota Iron Company.

CLASTICS ASSOCIATED WITH THE IRON-BEARING FORMATION.

There is only one place in the Vermilion district at which the clastic rocks are associated with the iron formation in such a way that no question can be raised that they belong together and that there is a gradation from the one into the other. This place is just south of the north quarter post of sec. 7, T. 62 N., R. 13 W., on the south slope of a hill. At this place the narrow bands of iron formation are interbanded with bands of conglomerate and slate. There are evidently several series of these bands, although it is possible that there may be in places a reduplication due to the close folding. The conglomerate is made up of fragments derived from the immediately subjacent greenstones, and as these fragments grow smaller the sediments grade upward through graywackes into finely banded greenish slates, next to which occurs the iron-bearing formation, consisting of chert, jasper, iron ore, and an occasional band of material that may correspond to the finer-grained slates adjacent.

Somewhat similar conditions were observed on the hill in the NW. $\frac{1}{4}$ of the SE. $\frac{1}{4}$ of sec. 10, T. 62 N., R. 14 W., which overlooks the large swamp to the northwest, although the proof of the relationship is, perhaps, not quite so clear. Here there is a large exposure of jasper in which a shaft has been sunk and through which a considerable quantity of pyritiferous ore has been hoisted. The jasper is followed to the south by a fragmental rock made up of fragments of greenstone. This is about 10 feet distant from the jasper. The fragmental rock is thoroughly impregnated with partial pseudomorphs of limonite after pyrite. South of this fragmental occurs an amygdaloidal lava. The sediments and the greenstone are both slightly schistose, the schistosity striking about east and west. South and west of this locality a number of other exposures of greenstone, associated with a fragmental rock made up of greenstone fragments, was observed. In none of the sediments could well-marked sedimentary banding be found.

THE IRON-ORE DEPOSITS.

HISTORICAL SKETCH.

The first mention of the occurrence of iron ore in the Vermilion district was made by J. G. Norwood, who observed it during his explorations in 1850 and published a statement concerning it in the report accompanying that of D. D. Owen.[a] The iron that he observed is that which occurs near Gunflint Lake, at the extreme east end of the district, and which geologically belongs with the ores of the Mesabi range. In this part of the Vermilion district the ores have never been exploited to any extent and are at present of no commercial importance.

Interest in what is now known as the Vermilion iron-bearing district was aroused in the sixties by the reported occurrence of gold in the slates and schists in the region of Vermilion Lake. There was considerable excitement for several years and a small rush to the district. Shafts were sunk and stamp mills were erected, the machinery having been packed in from Duluth, partly on the backs of Indian packers, over the Vermilion trail. A town site was laid out near Pike River, at the southwest extremity of Vermilion Lake, and some buildings were erected. In all a good deal of money was fruitlessly expended, as no gold deposits of any importance were found.

A reference to the possible occurrence of hematitic iron ore in the Vermilion district, in the strict sense, was made in Hanchett and Clark's report for 1865. The State geologist says:

> Specimens of hematitic specular iron ore were obtained from a heavy deposit said to lay between a lake forming the affluence of the upper Embarrass River and Vermilion Lake. The precise percentage of commercially pure iron contained in this ore has not been ascertained.[b]

A more detailed mention of the occurrence of the iron ore on the iron range at Vermilion Lake was made by H. H. Eames, who investigated this district in regard to the reported occurrences of gold and silver and described the iron-ore deposits as follows:[c]

---

[a] Report of the Geological Survey of Wisconsin, Iowa, and Minnesota, by D. D. Owen, 1852; Report of J. G. Norwood, p. 417.

[b] Hanchett and Clark: Report of the State geologist, Aug. H. Hanchett, M. D., together with the physical geography, metallurgy, and botany of the northeastern district of Minnesota, by Thomas Clark, assistant geologist, St. Paul, 1865, p. 6.

[c] H. H. Eames, Report of the State geologist on the metalliferous region bordering on Lake Superior, St. Paul, 1866, p. 11.

The iron range of Lake Vermilion is on the east end [of the lake], on the stream known as Two River, which is about 60 feet wide. There are two parallel ridges forming the boundary of this stream, and at the mouth on each side are extensive tamarack swamps. This range is about one mile in length, it then ceases, and after passing through a swamp, another uplift is reached, from 250 to 300 feet high. The iron is exposed at two or three points between 50 and 60 feet in thickness; at these points it presents quite a mural face, but below it is covered with detritus of the overcapping rock. On this account its exact thickness could not be correctly ascertained. The ore is of the variety known as hematite and white steely iron, and is associated with quartzose, jasperoids and serpentine rocks. It generally has a cap rock from 3 to 20 feet thick. A little to the north of this is an exposure of magnetic iron of very good quality, forming a hill parallel with the one described.

The hematitic iron has a reddish appearance from exposure to atmospheric influence; its fracture is massive and granular; color, a dark, steel gray. The magnetic iron ore is strongly attracted by the magnet and has polarity; is granularly massive; color, iron black.

The timber here is very abundant and good, of the same class as prevails elsewhere in this region.

Some time after this, in 1875, the first exploratory work in this district was taken up by Mr. George R. Stuntz, accompanied by Mr. John Mallmann, who began to prospect the Vermilion ore deposits on Lee Hill, southwest of the bay of Vermilion Lake, which is now known as Stuntz Bay, named after Mr. Stuntz. In 1880 Prof. A. H. Chester examined the Vermilion Lake ore deposits for private parties, and Mr. Bailey Willis studied them for the Census Office. Systematic and extensive efforts were made in the late seventies and the early eighties to develop the iron resources which were known to be present in this district. By this time the Minnesota Iron Company had been organized and all of the properties which at that time were known to contain ore and great stretches of country which were in the continuation of the ore range had been purchased, the company owning over 20,000 acres of land on the Vermilion range proper and in the vicinity of the good harbor on Lake Superior, known now as Two Harbors. On August 1, 1884, the Duluth and Iron Range Railroad was completed from Two Harbors to Tower. This road was 72 miles long. At a later date it was connected with Duluth, 25 miles away. During the first year (1884) 62,122 tons of ore were shipped, some of this having come from the stock piles which had been growing during the years of development preceding the opening of the railroad.

Prospectors were busy in the years prior to the opening of the railroad in prospecting the range to the east of Tower, and in 1883 outcrops of ore were found by Mr. H. R. Harvey in sec. 27, T. 63 N., R. 12 W. The body of iron ore indicated by these outcrops was further tested in 1885–86 and led to the opening up of the great deposits at Ely on which are now working the Chandler, Pioneer, Zenith, Sibley, and Savoy mines. During 1888 there were shipped from the Chandler mine 54,612 tons of high-grade ore.

From this time on the development of the range was rapid, as is shown by the annual increase in the shipments of ore (pp. 242–243).

ORE HORIZONS.

The iron-ore deposits of the Vermilion district show a striking analogy with those of the Marquette district. Like them, they may occur in two positions with respect to the iron-bearing formation. They are found, first, at the bottom of this formation and, second, within it, the ores in both cases being the same in character. The ores occurring at the bottom of the iron formation rest immediately upon the Ely greenstone, which thus forms the foot wall, and are overlain by and grade up into the jasper and associated rocks of the iron-bearing formation, which usually forms the hanging wall. Ores occurring within the formation either rest upon some impervious part of the formation above its base or else lie in the midst of the iron-bearing rocks, their position being determined by certain factors which will be discussed below. Workable ore deposits are known at two localities—Soudan and Ely. At Soudan there are a number of deposits belonging together, so far as mode of occurrence is concerned, and they are worked through a number of shafts, all belonging to the Minnesota Iron Company. With these ore bodies belongs that deposit of the old North Lee mine on Lee Hill, near Tower, the ore of which has long since been exhausted. At Ely there are two and possibly three ore bodies lying in an approximately east-west line, and exploited by the Minnesota Iron Company by means of a number of shafts. Future developments may show that these ore bodies are actually continuous and form one immense body of ore.

THE ELY IRON-ORE DEPOSITS.

DEPOSITS OCCURRING AT THE BOTTOM OF THE IRON-BEARING FORMATION.

To this group belong the deposits occurring near Ely, now worked by means of the shafts of the Chandler, Pioneer, Zenith, Sibley, and Savoy mines. The particular deposit upon which the Chandler and Pioneer mines

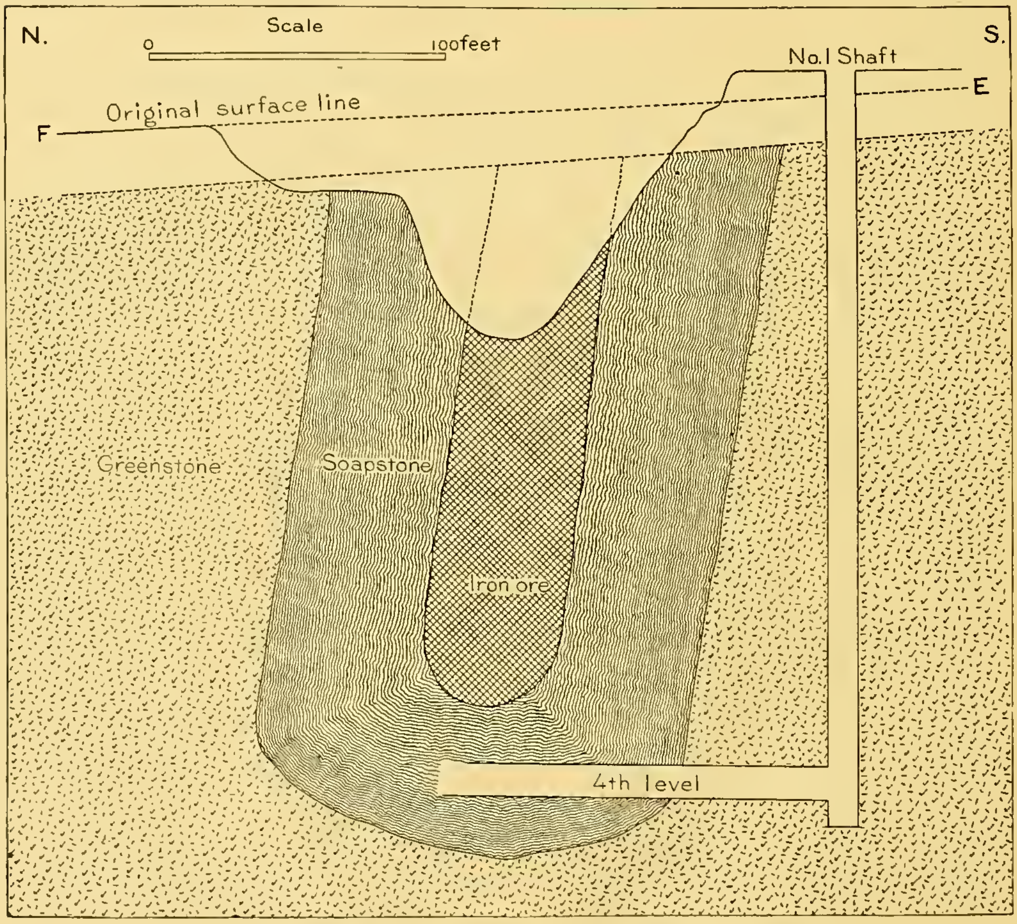


Fig. 8.—Vertical section across Chandler ore body along line E–F of fig. 9.

are working will probably prove to be one of the largest continuous bodies in the Lake Superior region (Pl. VIII). This particular ore body affords so perfect a confirmation of the law of the occurrence of ore deposits as stated by Van Hise that it is of very great scientific as well as economic importance, and will therefore be described in some detail.

PANORAMIC VIEW OF THE ORE BASIN NORTH OF ELY SHOWING SHAFTS OF THE CHANDLER AND THE PIONEER MINES

In the center of the picture is seen the great open pit caused by the [illegible] by open [illegible] which has been subsequently enlarged by caving

The workings at the Zenith, Sibley, and Savoy have not been extended far enough to enable a final statement to be made as to the shape of these ore bodies or the exact structural conditions under which they exist, or, indeed, to warrant a positive statement that they may not eventually be found to be connected with one another and possibly also with the Chandler-

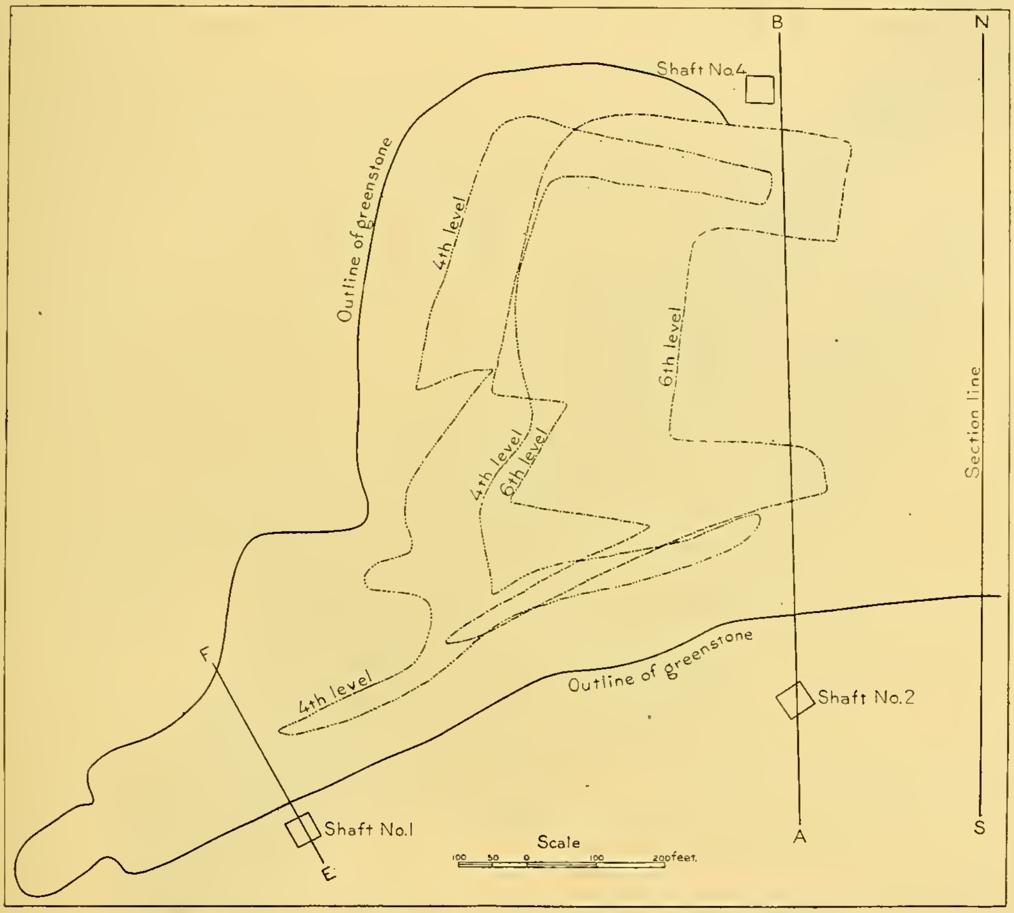


Fig. 9.—Horizontal section through fourth and sixth levels of the Chandler mine.

Pioneer ore body. The Chandler-Pioneer ore body, as well as the ore bodies to the east, occurs at the bottom and comes part way up the sides of a narrow canoe-shaped synclinorium whose axis trends about 80° E. The rocks in this vicinity have been very closely folded, and, indeed, slightly overturned, so that at the west end of the Ely trough both walls dip at a very high angle to the north. As the result of underground work, it is found that the south wall dips at an angle of about 70° N. The north wall ranges from a vertical position to a dip of 80° to the north. However, this northerly dip does not continue throughout the trough, but, on the contrary, it is found to be reversed at the east end of the trough, where the walls are overturned in the opposite direction to the walls at the west end, and now

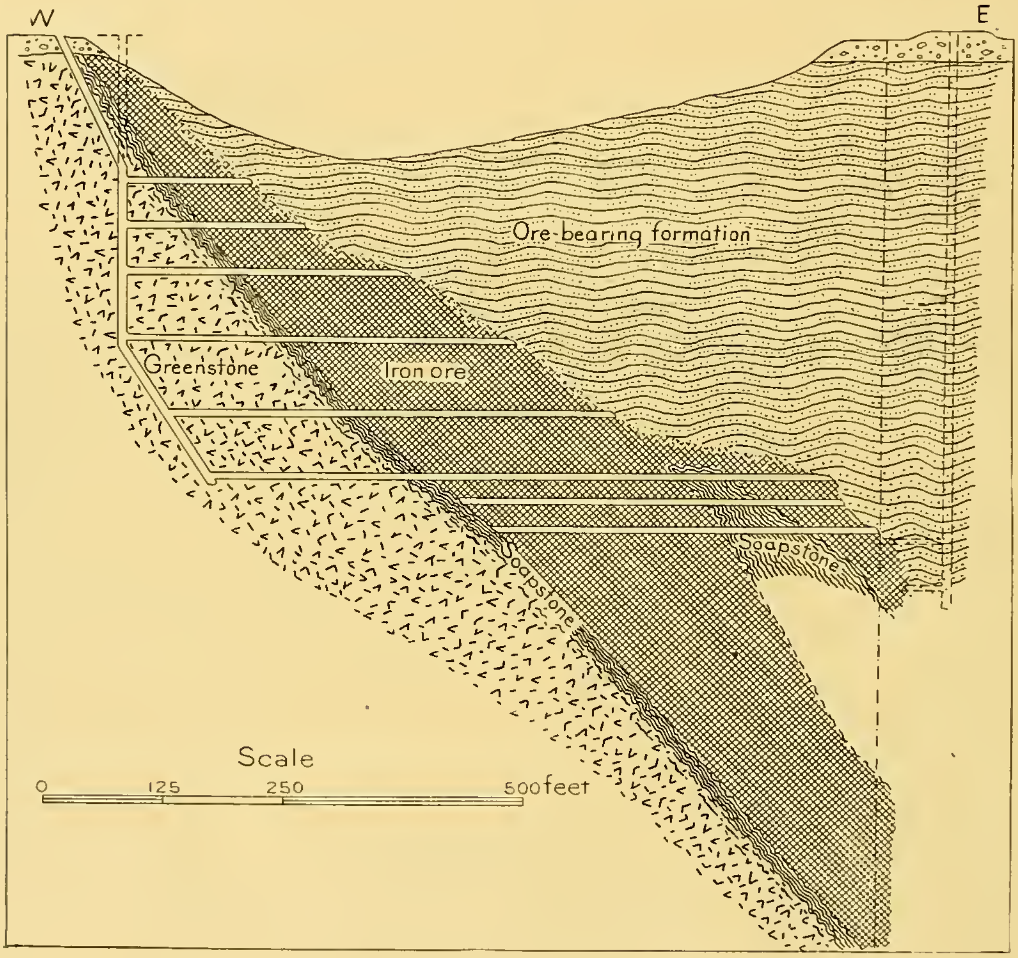


Fig. 10.—Vertical east-west section through the Chandler mine.

dip at a high angle—about 80°—to the south. It is not known exactly at what point in the trough this change takes place. It probably occurs about the center of the trough, near the east side of the Pioneer property. This reverse of dip is possibly caused by the occurrence of a small subordinate cross anticline, which has produced a warping in the strata, with an eastward pitch. These facts are shown by the accompanying illustrations. In fig. 8, a vertical section across the extreme western end of the basin, there is shown a narrow syncline with both foot and hanging walls dipping to the north. In fig. 9 there may be seen horizontal sections through the fourth and sixth levels of the Chandler mine, with position of section shown in fig. 11, indicated by line A–B. From study of this figure in comparison with figs. 8, 10, and 11 we see that farthest west and nearest the surface the syncline is narrowest, that as we go down we are compelled to go eastward to follow the base of the ore body (which therefore pitches eastward) and that the ore body widens very considerably.

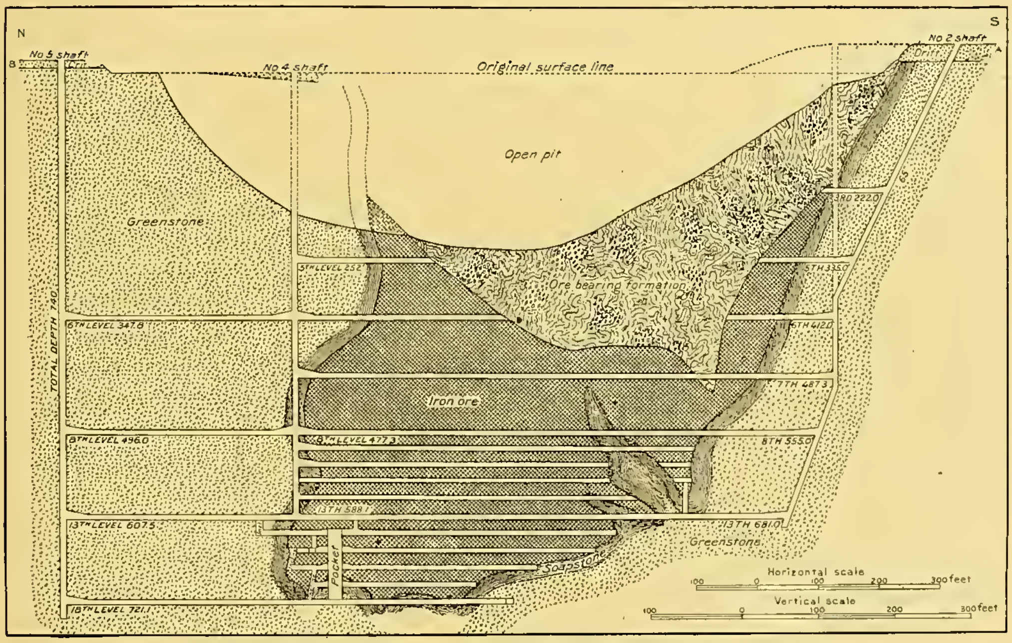


Fig. 11.—Vertical section through the Chandler mine along the line A–B of fig. 9.

North of the southernmost narrow syncline there is an eastward-projecting tongue of greenstone which indicates a subordinate anticline with a second syncline lying north of it and en échelon with the southernmost syncline. The workings of the mine where they extend to the bottom of the ore deposit (fig. 11) show the conditions which exist there.

From this section we see that the bottom has not a simple basin shape, but in section from north to south shows several subordinate rolls. These are indicated also by the irregularities of the western foot wall, which, instead of showing a smooth surface of paint rock, projects to the east in several more or less prominent tongues. The horizontal plans of the various levels show that these tongues project farther and farther eastward as the deeper and deeper levels are reached. By the time the eighth level is reached the tongue there shown is relatively narrow. It is possible that it may die out before it goes much farther east, and it is very probable that another small roll will be found to begin north of and en échelon with it. This irregularity in the western foot wall of the Chandler basin is well brought out by the mining operations. The drifts which have been put in to open up the west end of the ore body run in the paint rock (altered greenstone), and have been maintained along a course which carries them approximately parallel with the margin of the ore body. As a result they have a winding course. One going through these and keeping his course may see that he follows the tongue to the east, bends around this projection in the paint rock corresponding to the anticline, and then follows back west around the succeeding syncline of ore. Occasionally when the syncline of ore is very narrow the drift may cut directly across it, and in such instances a small tongue of ore surrounded by the paint rock is shown in cross section.

The foot and hanging walls of this overturned syncline, as well as the western wall and the bottom of the basin, so far as is known from the mining work, are of paint rock or soap rock. This soap rock is identical in character with the more or less schistose amygdaloidal and ellipsoidal greenstones which occur in such abundance upon the surface in the vicinity of Ely, and are found surrounding the north, east, and south sides of the Chandler basin in the numerous exposures. This greenstone, as has been already stated, is an altered basalt (see p. 152). Where the greenstone lies in contact with the jasper and ore it is almost invariably very schistose as the result of movements which have taken place between rocks of such different physical characters, and which have been more effective along this plane than elsewhere. Moreover, since such plane of contact represents a direction of easy flowage for the percolating waters descending from the surface, the rocks here have been subjected to leaching and have undergone very great metasomatic changes. As a result of these changes the minerals of these rocks have in places been altered to chlorite, the formation of which has produced a soft schistose rock. The soft, soapy feel of the rock causes it to be spoken of by the miners as soap rock or soapstone. With the other changes there has almost invariably been an infiltration of iron oxide to a greater or less extent. Consequently this contact phase of the greenstone is usually impregnated with iron oxide and thereby colored red. To this fact the rock owes its name of paint rock, a term which is very generally used by mining men for such altered and red rocks. The plane of contact between the ore formation and the greenstone has also been a plane along which actual movement has taken place, and as a result a zone of brecciation has been produced which includes a certain thickness of both the iron formation on the one hand and the soap rock or greenstone upon the other. The thickness of this zone varies greatly. In some places practically no brecciation has taken place, but in others there is a considerable thickness of brecciated rock. The production of slickensides along these cracks indicates movement even in the greenstone at a considerable distance away from the immediate line of contact with the iron formation.

Immediately adjacent to the greenstone, and showing with it the above-described irregular contact surface due to folding, lies the ore. Upon this ore lies a capping of jasper. Both the ore and the jasper are very much cracked, being penetrated by innumerable fractures, as is also the greenstone, though, as a result of its brittle character, the cracks in the iron formation are far more numerous and less continuous than those in the greenstone. This fractured condition of the iron formation is clearly due to compression resulting from the production of the close synclinal fold in which the formation lies. Hence, since the ore as well as the jasper is brecciated, there is no escape from the conclusion that the ore must have been formed, in great part at least, prior to the time of the last folding of the district which caused the fracturing of the rocks. The ore has been very much broken up, and this breaking has been a great boon to the mining company, as it makes it relatively easy to mine. For this reason, as has already been stated, the ore is frequently designated a soft ore, although this is, in a strict sense, a misnomer. In reality the various fragments of the breccia are fragments of hard ore. This natural brecciation has been taken advantage of by the efficient manager, and the system of mining which has been developed here merely continues the natural process of brecciation, and thereby the cost of winning the ore is greatly reduced. The method of mining employed in the Chandler is described and illustrated on page 240.

The plane of contact between the ore and the jasper agrees in general with the contour of the basin (fig. 11). One noticeable feature is that this plane of contact in the upper part of the basin dips on the south side to the north, and on the north side of the basin to the south. The conditions, in other words, are those of a normal syncline. As the deeper workings of the mine are reached, however, this dip is found to be overturned, and upon the north side the dip of the plane is to the north. It will be noticed that the greatest depth of ore lies, as it normally should, in the center of the basin. The ore follows up both the north and the south limbs of the syncline; it goes higher, however, and is very much broader on the south side than on the north side. This condition of occurrence is in accord with the view held concerning the origin of the ore deposits, and will be referred to below. The plane of contact between the jasper and the ore is irregular in the extreme, no sharp line of demarcation existing between them. As has already been intimated, the merchantable ore grades upward into lean ore, which in its turn merges by imperceptible gradations into the jasper, with very small quantities of interlaminated iron-ore bands. Bodies of jasper varying from minute pieces up to large masses project downward into the ore. Occasionally a horse of jasper is included in the ore. Again, a body of ore will project upward across the line into the jasper. Within this lean ore, or mixed ore and jasper, one can find pieces of jasper showing partial change into the ore, the banding of the jasper still existing in a more or less perfect condition in the ore. There is in reality no sharp line between the ore and the jasper, but there is a gradual transition from one to the other. These facts will be referred to again under the discussion of the origin of the ore deposits, on page 230.

THE TOWER AND SOUDAN DEPOSITS.

Let us now consider the ore deposits at Tower and Soudan. At these places the conditions of occurrence are not nearly so simple as at Ely. In the first place, the iron formation in the western part of the district has been very much crumpled, and there appear to be many alternations of jasper and a schistose green rock. The relations of the jasper and this green rock are not in all places clearly shown. At some localities it appears that the green rock is a greenstone belonging with the Ely greenstone, and hence the basement on which the jasper rests. It owes its alternation with the jasper to the intricate infolding and subsequent truncation of the two formations. In other places the evidence is fairly conclusive that we have to deal with dikes which were intruded both parallel to the banding of the jasper and across this banding. In both cases folding subsequent to their intrusion has brought about structural relations similar to those existing between the jasper and the basement greenstone. The rock forming the dikes which cut the iron formation is now uniformly green, except where discolored by the iron. Its chief component at present is chlorite, but certain facts—for instance, the presence of quartz phenocrysts, which were observed and which will be considered in detail at a more fitting place—show very conclusively that at least some of these dikes were originally acid intrusives. The alterations that these acid rocks have undergone have produced schistose rocks, which now are strikingly similar in macroscopic characters to some of the greenstones derived from rocks of an originally basic character. These dike rocks have been classed as basic rocks—greenstones. In one case—that of the schist at the Lee mine—Smyth and Finlay[a] state specifically that it has been derived from a quartz-porphyry.

DEPOSITS OCCURRING AT BOTTOM OF THE IRON FORMATION.

We have no conclusive evidence that any of the deposits of iron ore at Soudan or Tower rest upon what is the actual basement greenstone. Such an occurrence, if recognizable, would be found to be similar in all essential characters to the occurrence of the ore at Ely. We would find the ore at the bottom of a synclinal trough of the iron formation, with the greenstone forming the impervious bottom and sides of the trough. It is impossible to recognize with certainty the true basement greenstone on account of the intrusion of acid sills and dikes in the iron formation in the mines in the vicinity of Soudan and Tower; on account of the intricate and intimate relationship existing between these two kinds of rocks, due to this intrusion and heightened by the subsequent infolding of the eruptive and the iron-formation rocks; and also on account of the resemblance of the altered acid rocks to the greenstone. The deposits at the east end of Soudan Hill, which have been mined out, are supposed to have been laid

[a] The geological structure of the western part of the Vermilion range, by Henry Lloyd Smyth and J. Ralph Finlay: Trans. Am. Inst. Min. Eng., Vol. XXV, 1895, p. 639.

down in synclines upon the basement greenstone, and hence to belong to the same class of deposits as do those occurring at Ely. The one mined from the old pit known as the North Lee mine is presumed also to have been a deposit in an analogous position.

DEPOSITS OCCURRING WITHIN THE IRON FORMATION.

The deposits within the iron formation may be of two modes of occurrence: (*a*) They may have jasper both as a foot and hanging wall, and hence may lie within it and grade in all directions into it (these deposits are of small size); or (*b*) they may have paint rock (soapstone, or soap rock, as it is indifferently called by the miners) as foot wall, below which is again jasper, with similar paint rock or jasper as the hanging wall. Of this latter character, with an occasional pocket of ore lying wholly within the jasper, are the deposits worked at Soudan. The ore deposits showing the different modes of occurrence just mentioned are of very irregular shape and vary greatly in size. Masses of greenstone project from them into the jasper as a result of the irregularities of the foot wall, due chiefly to folding; or the plane of separation between the ore and the jasper is very irregular and projections of jasper extend down into the ore, and the ore extends into the jasper, such irregularities rendering the mining very uncertain and expensive. Occasionally great horses of jasper occur in the midst of an ore deposit.

The deposits occurring within the iron formation are far less likely to be as large and as continuous as those which lie at the bottom of the formation and rest upon an impervious basement, for the reason that the deposits occurring within the iron formation owe their existence to the introduction of igneous rocks in the form of sills or dikes, or to the peculiar conditions of fracture. Where the dikes are numerous there may be a number of relatively small deposits separated from one another by intervening walls (subordinate dikes) of soap rock or paint rock of varying thickness. This condition is well illustrated in the case of the ore deposits on Soudan Hill, which are being mined by the Minnesota Iron Company.

In structure Soudan Hill is a large anticline trending a little north of east and pitching steeply to the west. The summit of this anticline is occupied by a syncline having the same strike and pitch as the anticline, and it is within this syncline that the deposits occur. Before the jaspers were as intricately folded as at present they were intruded by dikes and sheets of acid rocks similar in composition and general character to those now outcropping on the islands and shores of Vermilion Lake. These sheets of igneous rocks were intruded essentially parallel to the bedding of the jasper, and were at varying horizons in the jasper, and hence are separated by varying vertical distances. The intrusion of these sheets has thus divided the iron formation, as it were, into a number of bands of different thickness. The dikes which cut through the iron formation are of varying trend, and these, as well as the intercalated sheets, were intruded in the iron formation at various angles with the horizon. When, after their intrusion, the rocks were folded, the intrusive sheets behaved essentially as intercalated beds in the iron formation and were crumpled with it into close synclines and anticlines. When the folding took place the brittle jaspers accommodated themselves to the movement by fracturing, whereas the less brittle eruptive rock accommodated itself by shearing.

Owing to the fractured character of the associated iron formation the downward-percolating waters passed readily through it, but were stopped and led along the relatively impervious acid igneous rocks. These were thus intensely affected by the circulation of the water, which, bringing iron in large quantity in solution, deposited considerable quantities of it in the igneous rocks during their alteration. As a result of the action of the percolating waters these rocks were intensely altered chemically. The addition of iron rendered possible the formation of the chlorite, which is not as a rule characteristic of the alteration of acid rocks. Now these intrusives are essentially the same in general appearance as the soapstone and paint rock derived at various places from the basic greenstones. From the point of view of their influence in the formation of the iron-ore deposits they are also absolutely identical with the above-mentioned soapstones, originally of basic character, and they will be designated as soap rock and paint rock, in accordance with the custom of the miners.

Occurring in the way described, in the large central syncline of the iron formation, these eruptive sheets have divided it into a number of small synclines, each with an essentially impervious basement of soap rock. The sheet of rock forming the impervious bottom of one trough forms the impervious top to the next lower synclinal trough. Between these lie the intensely fractured rocks of the iron formation. Through these fractures downward-percolating water carried the ore and deposited it upon the impervious bottom of the troughs formed by the intercalated igneous sheets. Hence it comes about that the ore deposits, being derived from only the small quantity of iron formation which occurs between these adjacent sheets, are relatively small, and for the most part disconnected. They occur, however, in a syncline, as does the enormous Chandler-Pioneer deposit of Ely, the essential difference being that at Soudan the ore body in the syncline has been separated into a number of irregular bodies, the one above the other, instead of occurring in one continuous ore deposit.

One might infer from the above statement that these sheets were introduced very regularly into the iron formation. This would be an incorrect inference. Anyone familiar with igneous phenomena knows that the dikes and sheets divide more or less frequently at irregular intervals. They have done so in Soudan Hill, so that we may find deposits joining other deposits as a result of the disappearance of the subdividing sheet as we go away from the point where it leaves the main mass, or a large deposit will divide into two or more small ones as a result of the introduction of such an offshoot from a sill. Hence there may be a very remarkable irregularity in the occurrence of the ore deposits formed in such synclinal basins where the impervious bottom is due to the presence of intrusive sills. A further cause of irregularity is the introduction of the more or less vertical dikes which were contemporaneous with the introduction of the sills. These, cutting through both sills and the associated iron formation, have still further tended to subdivide the rocks into masses of varying size. Furthermore they, like the iron formation, were much folded, and now occupy various positions and are of greater or less importance in determining the size of the ore bodies. Thus, for example, if a dike should have cut across a sheet at nearly right angles, and in such a way that when the two were folded a pocket with nearly impervious bottom and sides was formed, an ideal condition would have been produced for the deposit of ore, according to methods described by Van Hise in numerous articles to which reference has already been made. The larger the pocket the larger, other things being equal, would be the deposit of ore.

Belonging with the ore deposits occurring within the iron formation are certain small deposits of relatively slight commercial importance, but of considerable scientific interest. These deposits are those which have the first mode of occurrence mentioned above. They are surrounded on all sides by jasper. Hence their occurrence does not depend on the formation of a synclinal trough with impervious bottom, as in the previously considered cases. These deposits, as a rule, form so-called chimneys of ore, having in general, as the name indicates, a rectangular outline, and their origin is evidently due to the presence of fracture planes or zones in the jasper. Along these zones water has percolated and has produced the ore bodies from the iron formation by the well-known process of replacement, the ore diminishing in richness as the distance from these fractures increases.

ORIGIN OF THE ORE DEPOSITS.

Having now described the manner of occurrence of the ore deposits and shown their relation to the geologic structure, we are prepared in the light of the facts given to consider their origin. The origin of ore bodies completely surrounded by jasper obviously depends on the occurrence of fractures, for the ore is confined to the vicinity of the fractures and diminishes in richness as the distance therefrom increases. The importance of these fractures as channels for downward descending waters is also obvious. Hence the connection between the occurrence of the deposits and the action of percolating water is shown. This interdependence is further impressed upon one when a study is made of the cross section of the narrow ore deposits of Soudan, and also of the cross section of the Ely trough. It will be readily recognized that the plane of contact between the two formations will, as a rule, perform the same function as any large, continuous fracture in the formation itself, in that the plane of contact will permit more readily the passage of water, since it has a continuous line of weakness, than will the small, discontinuous fractures which may exist in the formation. Hence the ore deposits in this case will be confined more or less closely in their occurrence to this plane of contact. Where the converging streams of descending waters meet, at the bottom of the trough, the action has been most intense, and consequently the largest bodies have been accumulated there. Theoretical considerations show that if such a trough or other favorable place is to contain a large body of high-grade ore it should be a structural feature which has at some point or points exits for the inflowing descending currents of water. Since the accumulation of the ore depends on the circulating waters, of which some parts bring in and other parts cause the deposition of the iron, and since any given amount of water must carry an exceedingly small percentage of iron in solution, it is evident that the free circulation of large quantities of water must be an extremely important factor in the production of an ore deposit. The second great factor is time—a long period, in which complete replacement may take place, being more favorable than a shorter one. Of course it is here presupposed that there exist the other conditions necessary to the accumulation of the ore, which are the presence of iron-bearing material as the source of the iron and the structural features for its accumulation.

A full discussion of the chemical reactions which result in the deposition of the ore has already been given by Irving and Van Hise in the monograph on the Penokee series,[a] and the reader is referred to this for the details.

The following is a summarized statement of Van Hise's views of the general chemical process of concentration as the result of which this and similar ore deposits have been produced:

The next question to be considered is the chemical process of concentration of the ores. For places where waters from different sources are converged, this process has been fully given in Monographs XIX and XXVIII of the United States Geological Survey. In this paper the discussion will be only summarized. A part of the iron oxide of the ore was deposited in its present condition as an original sediment containing silica and other impurities. However, the nature of the sediment may have been changed—that is to say, it may have been deposited in part as iron carbonate, or in small part as iron sulphide or iron silicate, and later transformed to iron oxide in situ. The lean material originally deposited where the ore bodies now are has been enriched by secondary deposition of iron oxide. Briefly, the process of enrichment is believed to have been as follows:

The source of the iron for the enrichment of the ores is believed to have been mainly iron carbonate. Meteoric waters are charged with oxygen. As they enter the soil they would be dispersed through innumerable minute openings. The waters which early in their journey come into contact with iron carbonate would have their oxygen abstracted. Such waters would be likely to be those following circuitous routes. The deoxidation of the waters by the iron carbonate would produce ferruginous slates and ferruginous cherts. In this alteration the carbon dioxide would be

[a] The Penokee iron-bearing series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: Mon. U. S. Geol. Survey Vol. XIX, 1892, pp. 283–284.

liberated, and would join the descending waters. Thus carbonated waters free from oxygen would be produced. Such waters are capable of taking a considerable amount of iron carbonate and some iron silicate into solution. Large quantities of these solutions would be converged upon the sides or at the bottom of the pitching troughs, or in other places where there were trunk channels for water circulation.

After an iron-bearing formation was exposed to descending waters for a considerable time, a large part of the iron carbonate adjacent to the surface would be transformed to ferruginous slates and ferruginous cherts. This change would take place most extensively where waters were abundant and a somewhat direct course led to the trunk channels. After this process was completed at such places, the waters now following this direct route would pass only through the ferruginous slates and ferruginous cherts and would reach the trunk channels charged with oxygen. There the solutions bearing iron carbonate and those bearing oxygen would be commingled. Iron sesquioxide would be precipitated. Therefore the iron oxide of an ore body consists in part of iron compounds originally deposited in situ and in part of iron brought in by underground waters. The material deposited in situ may have been originally detrital iron oxide or it may have been derived from iron carbonate, iron sulphide, or iron silicate, which was oxidized in place, or from two or all of these sources. It has been assumed that the part brought in by underground waters was mainly transported as carbonate, although a portion may have been transported in some other form. Of the two sources of iron ores, the original material and that added by underground water, the latter is upon the average probably more abundant. But in some exceptional cases, where there is a large amount of detrital iron oxide, the material added by underground waters may be subordinate. However, in all cases it may be said that were it not for the secondary enrichment by underground waters, through the addition of iron oxide, the material would not be iron ore. The evidence of this lies in the fact that the ore bodies are universally confined to the places where underground waters have been converged into trunk channels.

The ore deposits contain upon the average a less quantity of silica than does the average of the iron-bearing formations. It follows therefore that silica must have been dissolved. This doubtless was largely the work of the great volume of water converged into the trunk channels. It has been seen that the waters which carried iron carbonate to the ore deposits were carbonated. The precipitation of iron oxide from carbonate liberated more carbon dioxide, so that the waters were very heavily charged with carbonic acid. In some of the districts basic igneous rocks occur within the iron-ore deposits or as basements to them. In all such cases these basic rocks are found to have lost a large part or all of their alkalies. These must have passed into the solutions. Hence the waters moving along the trunk channels would in some cases contain alkalies besides being rich in carbon dioxide. It is well known that such solutions are capable of dissolving silica. Therefore the conditions which result in the precipitation of iron oxide also furnish conditions favorable to the solution of the silica. Silica is thus largely dissolved from the ore bodies and transported elsewhere. The removal of the silica is ordinarily only less important in the development of the ores than the addition of the iron. In many cases the abstraction of the silica proceeded further than the deposition of the iron oxide, thus making the rocks very porous and further rendering the conditions favorable for abundant circulation.[a]

As the result of the detailed study of the ores in the various Lake Superior iron-bearing districts the conclusion has been reached that they are essentially replacement deposits, and this conclusion, pronounced early in the study of the district, has been strengthened by the observation of numerous facts in all the other districts which have been studied since then. The following facts from the Vermilion district alone seem to offer incontestable proof that this is the character of the deposits in this district, and also gives clear proof of the time of the formation of these deposits. Near the west end of the ore body worked from shafts No. 7 and No. 8 on Soudan Hill there is a large mass of jasper, already described by Smyth and Finlay,[b] lying directly across the ore with banding corresponding to and continuous with the banding of the adjacent ore. Again, on Lee Hill, along the south and west sides of the old North Lee mine, a breccia between the iron formation and the underlying schist has been produced. Some of the fragments of jasper in this breccia have been replaced by hematite with, however, a partial retention of the banded structure of the jasper. That the iron ore at this particular place was deposited later than the movement which formed this breccia is shown by the fact that the fragments of the breccia are cemented in many places by hematite ore, and numerous similar bodies may be seen which have been formed in cavities within the breccia. A study of the ore remaining in place at the North Lee mine and the adjacent banded iron formation also shows intimate connection between the two. The iron formation has an approximately east-west trend and seems to rest in a westward-pitching trough of chloritic schist, the schist occurring both on the north and south as well as at the east end of the iron formation. The ore body corresponds in trend with the strike of the formation itself, and on its south and west sides lies next to the iron formation, the banded jaspers. As the ore body is followed westward, the ore is gradually more and more mixed with jasper, becoming lean ore, and then the stringers of

[a] The iron-ore deposits of the Lake Superior region, by C. R. Van Hise: Twenty-first Ann. Rept. U. S. Geol. Survey, Pt. III, 1901, pp. 326–328.

[b] Op. cit., fig. 8, p. 42.

ore continue into the jasper, grower fewer and thinner, until finally the iron formation consists almost exclusively of jasper and chert, with but isolated narrow layers of ore in it. The banding of the jasper is seen to be continuous with that of the ore, which still possesses a banding, though an imperfect one.

At one place on Soudan Hill, north of open pit No. 6, a contorted banded iron formation is cut by a dike which runs nearly north and south, cutting across the bands of the formation (fig. 12). On the east side of

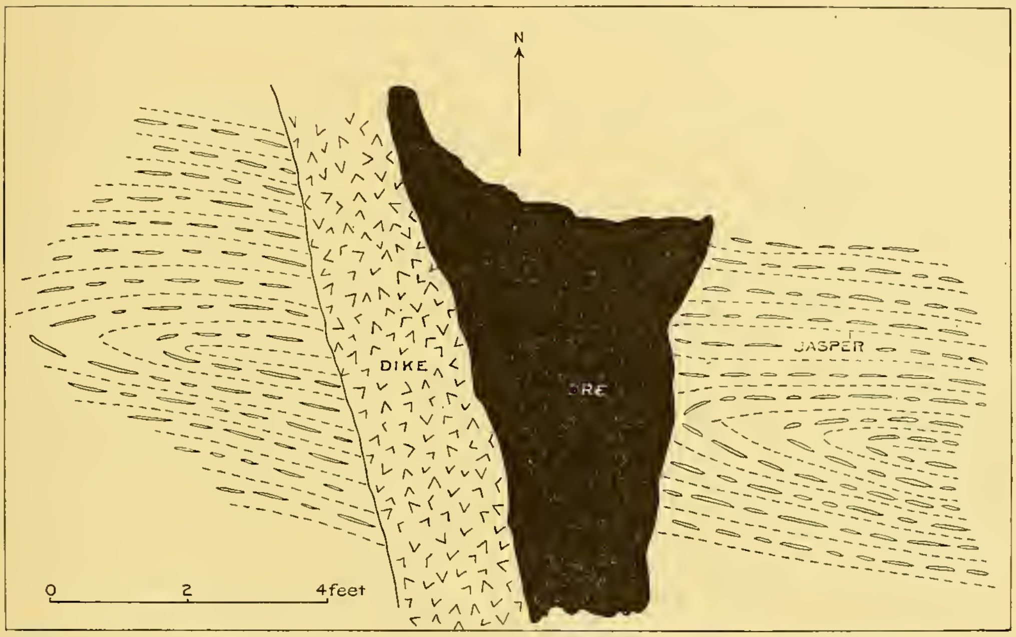


FIG. 12.—Reproduction of sketch showing replacement of jasper by iron ore. After Smyth and Finlay.[a]

the dike and between the dike and the jaspers and cherts there has been formed a small ore deposit. Here the banding in the adjacent jaspers and cherts appears to run right on through the ore, and although interrupted by the dike is found to be continuous beyond this.

At Ely the rock has been very much brecciated, but even there the banding in the ores and their intimate mixture with the bands of jasper seem to show very conclusively that their relation is essentially the same as that of the ores and jaspers at Tower and Soudan which have been

[a] Reproduced from The geological structure of the western part of the Vermilion range, Minnesota, by Smyth and Finlay: Trans. Am. Inst. Min. Eng., Vol. XXV, October, 1895, p. 643.

described above. The only explanation as to the origin of the ore which appears to conform at all to the facts is that the ore is the result of a process of replacement, and that the original rock was a banded rock, either essentially the same as the present banded jasper or, as seems more likely, the same kind of rock as that from which the jasper itself has been derived by replacement. The presumed original nature of this rock has already been discussed (p. 191) and the conclusion reached that it was a cherty iron carbonate essentially similar to that described from the various iron-bearing districts of Michigan, and especially from the Penokee-Gogebic district of Wisconsin and Michigan.

An explanation of the ore as a chemical deposit[a] contemporaneous with the deposition of the remaining portions of the iron formation is, as Smyth and Finlay have already stated, altogether incompatible with the occurrence described above.

In the case of every known body jasper forms at least one boundary in some part of it, under such circumstances that the bands, if continued, would run into the ore. This fact, taken in connection with the tortuous form of many of the bodies, seems to us quite inexplicable on any theory of contemporaneous deposition of jasper and rich ore. For such a theory would involve the extraordinary assumption that the conditions of sedimentation or chemical precipitation were so radically different on opposite sides of an imaginary vertical plane in ocean water as to permit the contemporaneous deposition or precipitation of nearly pure silica on one side and nearly pure ferric oxide on the other, and that such differences in conditions persisted long enough to permit the accumulation, in some cases, of 100 feet or more of material.[b]

The theory that the ore is primarily the result of replacement by iron oxide of various substances,[c] notably iron, calcium and magnesium carbonates, and silica, and of accumulation of the replacement products in places especially suitable, the location of these places being due to geologic structure, is in direct accord with the facts which have been observed in the district, and which have already been discussed in considerable detail.

The time of the accumulation of the ore can be fixed approximately. It was subsequent to the folding which produced the synclinal troughs in which the ores are now formed. This folding was of course also

---

[a] The iron ores of Minnesota, by N. H. and H. V. Winchell: Geol. and Nat. Hist. Survey of Minnesota, Bull. No. 6, 1891, pp. 103-112; N. H. Winchell, Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 547.

[b] Smyth and Finlay, op. cit., pp. 643-644.

[c] Mon. U. S. Geol. Survey Vol. XXVIII, 1897, pp. 400-405.

partly instrumental in fracturing the brittle iron formation and rendering it thereby more permeable to percolating water, which was the agent which effected the accumulation. A consideration of the above fact further strengthens the theory that the folding and fracturing preceded the accumulation of the ore. That this accumulation clearly took place subsequent to this fracturing is furthermore proved by the fact that the fractures which traverse the iron formation have been frequently cemented by infiltrated iron ore.

In the case of the Tower and Soudan deposits there appears no evidence of folding subsequent to the accumulation of the ore deposits, for the ore is uniformly fairly massive; although such folding occurred. Moreover, we do not find in these deposits the micaceous hematites or schist ores which are found occasionally in the Marquette district of Michigan, and which owe their origin to the shearing to which they were subjected while they were so deeply buried that they were essentially in the zone of flowage and did not undergo fracturing, such as is produced under ordinary conditions.

The case is somewhat different, however, at Ely. There, it is certain, more or less extensive earth movements took place after the ore was deposited, for the ore and the overlying jasper are fractured through and through, so that they resemble in places a breccia; and since these ores are very thoroughly fractured, we conclude that the movement to which they owe this fracturing took place while the ores were relatively near the surface, or, in other words, were in the zone of fracture for the ore and the associated jaspers Had they been more deeply buried, micaceous hematites would have been produced, and the cost of exploitation would have been very much greater than it is at present. As it is now the ore is almost a rubble, and can be mined much more economically than can the massive ore at Tower and Soudan. It is interesting to note that subsequent to the formation of this rubble the ore, at least at the extreme east end of the Ely trough, has been cemented together by infiltrated material—iron ore to a certain extent, but also calcite and siderite to a still greater extent. Where this cementation of the brecciated ore has taken place, as, for instance, in the Savoy mine, the ore is almost as hard as that obtained from the Soudan mines.

From the above statements the impossibility of fixing the time of the formation of the ore deposits very definitely will be recognized. The process of folding was inaugurated between Archean and Lower Huronian time; but since the present attitude of the troughs in which the main ore deposits are located was mainly produced by the folding of the Lower Huronian, the replacement certainly occurred, for the most part, after Lower Huronian time. Since there are no pre-Cambrian deposits later than the Lower Huronian in this part of the district, the determination of the time of the replacement process can not be more accurately made. The process begun shortly after Lower Huronian time doubtless has continued, perhaps with interruptions, to the present time.

METHODS OF MINING IN THE VERMILION DISTRICT.

All of the ores of the Vermilion district are at present obtained by means of underground workings. The underground work follows one of two systems—either that known as the "overhand stoping" system, or that known as the "caving" system. Both systems have been modified in certain particulars, according to the peculiarities of the deposit or in agreement with the ideas of the management as to the most economical methods of exploitation. It would therefore be impossible to give in this place detailed descriptions of all the methods in use, as this would involve practically a description of the system followed in every mine in the district; but a brief space will be devoted to a description of the methods used at two of the typical deposits—the mines at Soudan, which use a system of overhand stoping, and the Chandler mine, of Ely, which is exploited by means of the caving system.

In the mines at Soudan the system of overhand stoping is best developed, and therefore these mines, and especially the workings of No. 8 shaft, may be regarded as a type of this system. The description which follows is in part an abstract of papers by Bacon[a] and by Denton[b] and of the statements of Mr. F. Ahbe, sometime mining engineer in charge of the mine, and in part is the result of personal observation by the author.

The ore at Soudan, which is a hard, blue hematite, occurs in great irregular bodies of more or less lenticular shape, which dip steeply to the

[a] Development of Lake Superior iron ores, by D. H. Bacon: Trans. Am. Inst. Min. Eng., Vol. XXI, 1892, pp. 299–304.

[b] Elements of methods of metal mining based upon Lake Superior practice, by F. W. Denton: Engineers' Year Book, University of Minnesota, Vol. IV, 1896, pp. 49–67.

north at angles ranging from 65° to 80°, and pitch to the west at an angle of 22° to 45°. As the result of this pitch, the deepest levels are farthest west. The deepest shaft, No. 8, was down 926 feet at the thirteenth level in 1902. Fig. 13, taken from Bacon's account referred to above, is a cross section through shaft No. 8, showing the condition of the Minnesota Company's mine, presumably about 1893, the time of the publication of the article. It shows the general arrangement of the workings. The ore bodies lie one above the other, and are usually separated from one another by impervious basements of "paint rock" or "soap rock." Sometimes they are partially surrounded by material of the iron formation proper, that is, the jaspers, cherts, and interbedded bands of hematite. When first opened up, the ore deposits were exploited by means of open pits. These were carried down to a maximum depth of 150 feet.

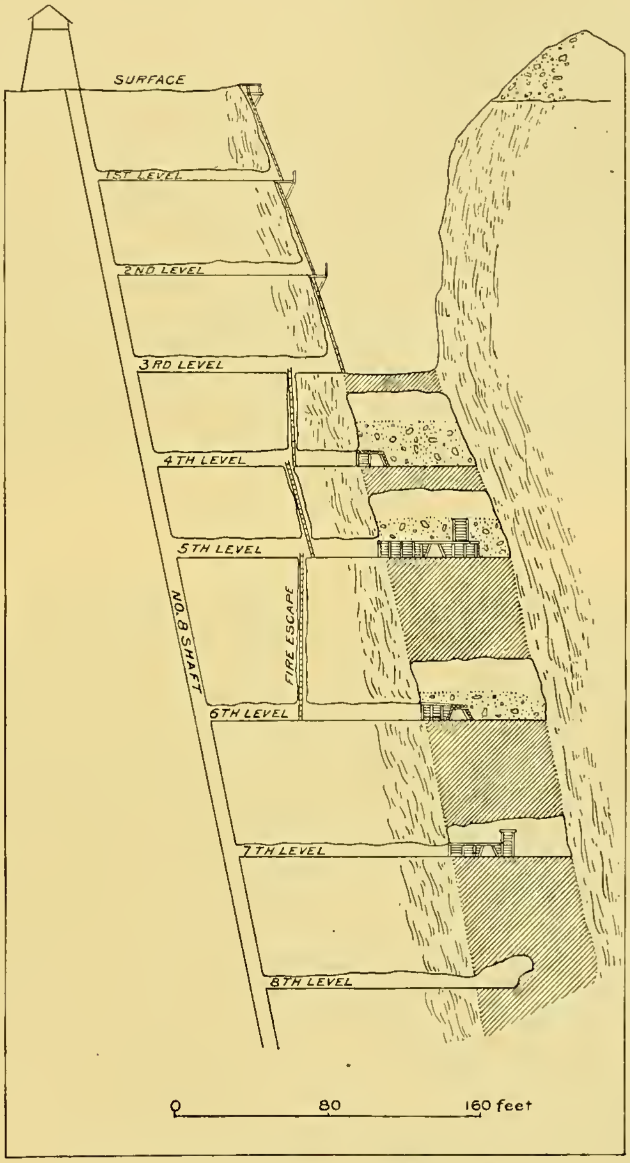


Fig. 13.—Cross section at No. 8 shaft, Soudan, Minn.

when it was found advisable to begin underground mining. From a shaft in the soap rock which forms the foot and hanging walls, crosscuts are run off at levels about 75 feet apart. From such a crosscut a slice of ore extending from the foot to the hanging wall, and from 15 to 20 feet thick, is removed or stoped out. When this has been cleared out, drift sets consisting of legs 9 feet long, and averaging 15 inches in minimum diameter, with caps 11 feet long and averaging 16 inches as the minimum diameter, with heavy lagging, are set up, running from the crosscut through the stope, usually near its center. Pl. IX, *A*, shows these main-level timbers being put in on the floor of the stope. After the timbering is completed, filling is begun. These drift-set timbers are apparently fully strong enough, as 80 feet of rock which is present over some of the drifts has not broken them. Fig. 14, a horizontal section through the fifth level of the Minnesota mine near its connection with the shaft, shows the

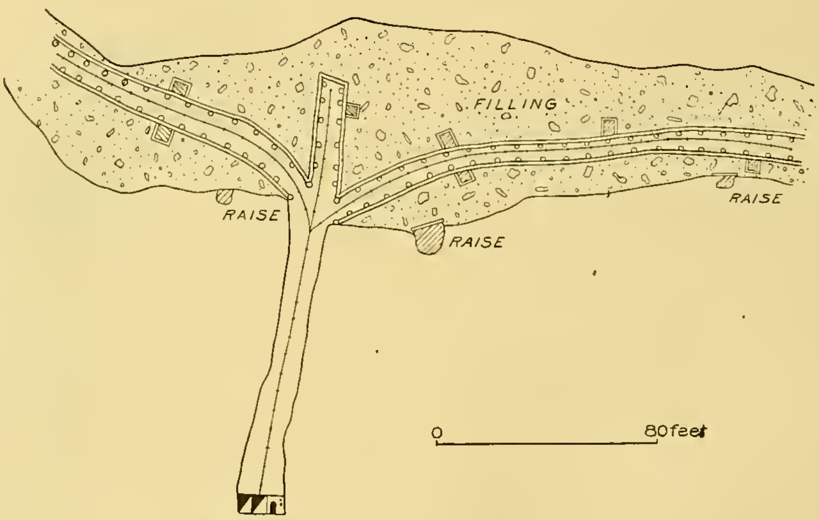
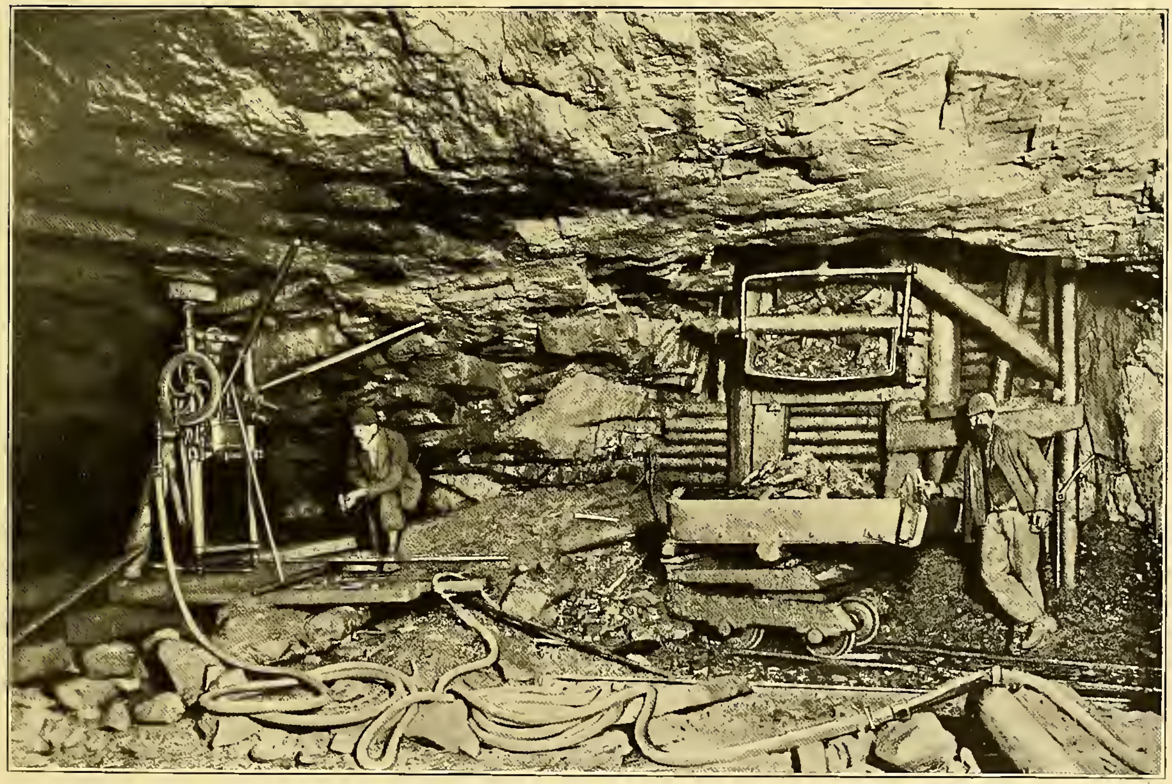


Fig. 14.—Horizontal section through the fifth level of No. 8 shaft, Soudan.

arrangement of the drifts and their connection with the crosscut in the foot wall connecting them with main shaft. On the main level the ladder ways and chutes or mills, 6 feet square, requiring timbers 7 feet long and averaging 12 inches in diameter, with a minimum of 9 inches in diameter, are timbered up a few feet above the drift sets. The space from which the ore has been removed is then filled and the drift sets covered with several feet of rock. Fig. 15 illustrates the way in which these fills are made, and shows how connection is maintained, by means of chutes and ladder ways, with the main drifts at the bottom of the level.

Pl. IX, *B* shows the top of one of the fills in the Minnesota Company's mine. In the background is seen the cribbed portion of the

A. MAIN-LEVEL TIMBERING, MINNESOTA MINE.



B. FILLING SYSTEM, MINNESOTA MINES, SOUDAN, MINN., WITH CHUTE FOR DISCHARGING REFUSE FROM UPPER LEVELS.

From photographs belonging to the Minnesota School of Mines.

raise, which passes through the level and from which rock for the filling is obtained, with a loaded tram car below its mouth. This raise extends upward through the foot wall, with ore forming the front side of the raise, to the level above, through which it passes in a cribbed way, and so on to the surface. Below the point shown in the figure the raise is cribbed, and is

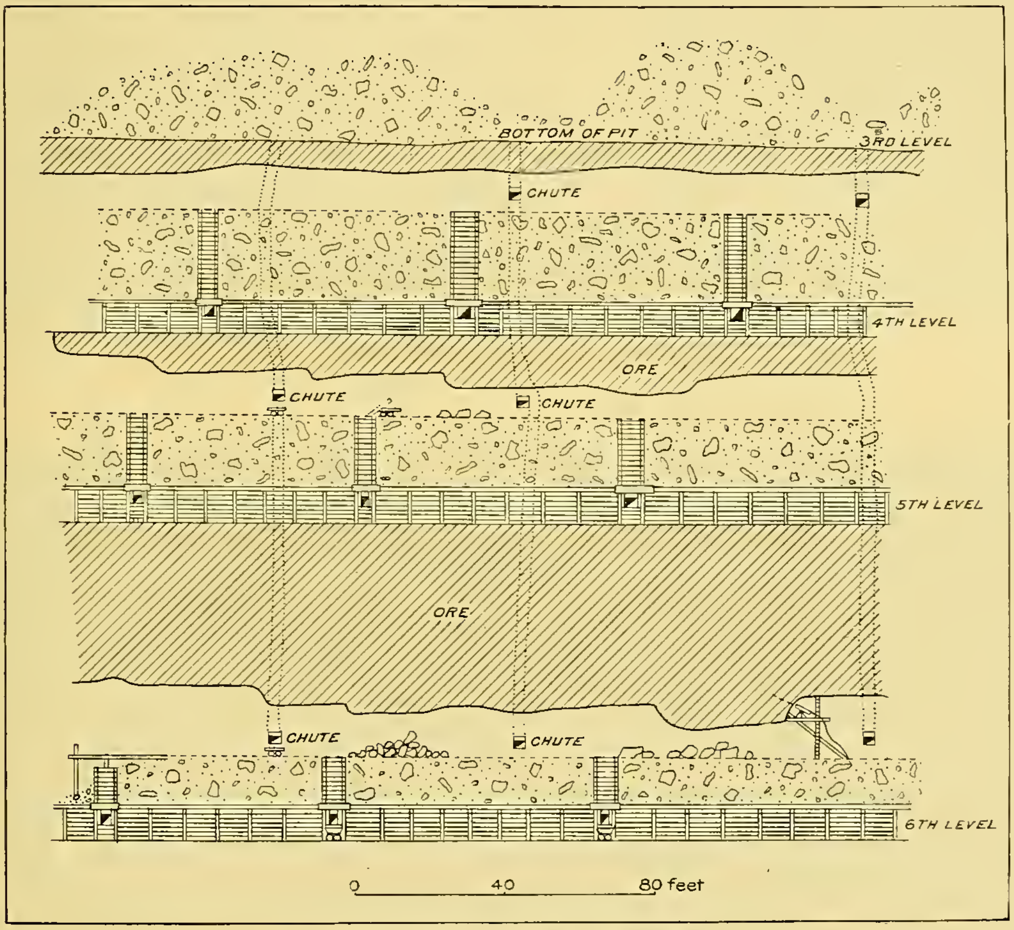


Fig. 15.—Longitudinal section through Soudan mine.

carried by this cribbing through the fills on the various levels below. To the left is shown a diamond drill, used in drilling holes in the ore forming the roof of the stope, into which dynamite is then introduced and discharged, bringing down enormous masses of the ore.

The rock for this filling is obtained from the raises which are cut in the soap rock at the foot or hanging wall, and which communicate from level to level with the bottom of the open pit. Such a raise passes through a level with its front face cribbed and an opening in the raise at the height at which it is desired to discharge the filling into the trams waiting for it. When filling is desired at any place the entire raise below that point is filled, and the filling then run through the opening in the cribbing at the proper place; or timbers and rails may be laid across the raise, making a floor, which prevents the filling descending below that point, and from this place it is then run out into the trams.

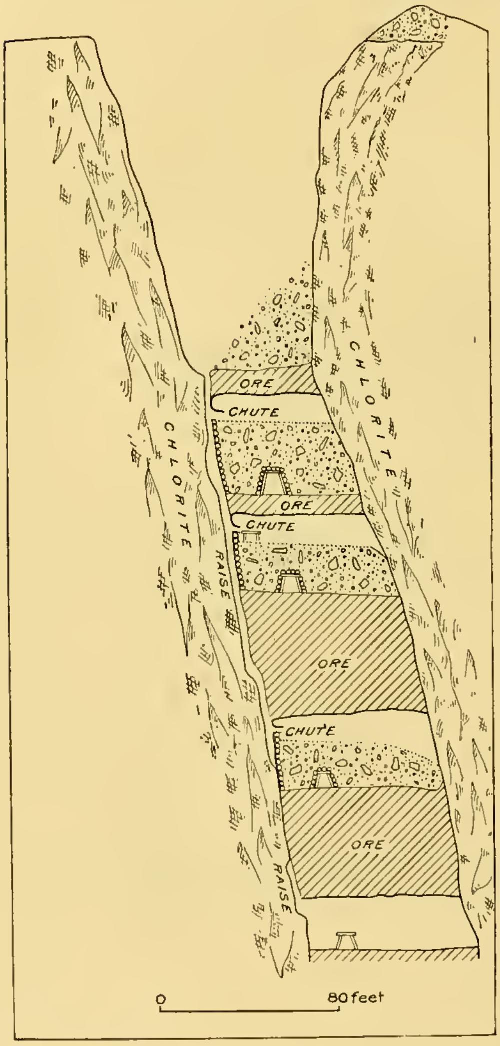


FIG. 16.—Cross section of Soudan mine showing raise.

Rock to fill the topmost level, or any other level being worked at the same time with it, is taken from the accumulations of loose material at the bottom of the open pit, derived from the caving in of its sides and from the drift at its surface, or else from material which has been blasted down from the walls of the pit. After the topmost level is worked out filling may be run down into the level below that, and so on down as the development requires it. Fig. 16 is a cross section through the Minnesota mine showing how the raise in the foot wall connects with the surface, and how connection is maintained with the levels at various heights as the filling proceeds.

Upon this filling the workmen stand, and here the drills are placed, mounted on braced cribbing, or in any other way that will give them a sufficiently firm foundation. This keeps the workmen near the roof, which is one of the advantages of overhand stoping, in that the roof can be easi'y examined and accidents from

A. VIEW SHOWING METHOD OF LOADING CARS.

B. VIEW OF MAIN DRIFT WHICH HAS BEGUN TO CAVE, CHANDLER MINE

From photographs belonging to the Minnesota School of Mines.

falls prevented by breaking down the rock as soon as it is observed to be loose. From the top of the fill the roof can readily be reached and a slice of ore about 10 feet in thickness is blasted down from it, broken up, and thrown into the chutes (mills). These chutes are 25 feet apart. Formerly they were much more widely separated, but experience has shown that the distance now maintained is the best. The men handling the ore which falls between can work both ways from the chutes and can throw the ore into the chutes without tramming or second handling. These chutes lead down to the drift below, and from them the ore is let out into the tram cars. Pl. X, *A* shows the method of loading these cars in the main drift at the bottom of one of the chutes. When filled the cars are hauled by mules to the shaft and thence hoisted to the surface. As the stope is extended filling is let in from the raises, and the chutes and ladder ways are extended upward to keep pace with the filling.

The ore is very hard and the cost of breaking it is high. Percussion or power drills are used to some extent, but diamond drills are more commonly used for boring the holes which are used in blasting the ore down. This is probably the only mine in the district in which the diamond drills are used for boring preparatory to blasting. It has been found that diamond drills are in the long run cheaper for this work than percussion drills.

After having been hoisted to the surface the ore is run through Blake crushers, which reduces it to sizes suited for furnace use. The ore is then run directly into cars during the shipping season, or during the winter season is piled in stock piles and loaded from these by steam shovels into cars when the shipping season begins.

The ore deposits at Ely are the most important and most interesting in the district. The oldest and most productive mine at Ely is the Chandler, in which the ore is mined on the caving system. The great body of ore that is exposed by the Chandler lies in a trough of greenstone which plunges to the east at an angle of about 45°. The continuation of this same ore body is worked on the caving system by the Pioneer mine to the east of the Chandler, which, since it is on the pitch of the ore body, gets all of the water from the Chandler. A layer of sheared greenstone discolored by iron (paint rock), 20 to 22 feet thick, lies between the ore and the comparatively massive greenstone. The foot and hanging walls of this paint rock dip to the north at an angle of about 70°. Figs. 10 and 11 are respectively vertical E.-W. longitudinal and vertical N.-S. cross sections of the Chandler mine showing the features here described. The ore is capped by fractured iron-formation material, jasper, chert, and ore bands, which is overlain by glacial drift. The ore body has been reached through five shafts sunk in the greenstone. The greatest depth is attained by No. 5 shaft, which was down in 1902 to the eighteenth level, at a depth of 740 feet vertically. All of the shafts were originally vertical, but shafts Nos. 2 and 4 were sunk so close to the ore body that the upper portion slid into the pit as the result of the caving. Inclined shafts with openings farther back from the pit were sunk to intercept the shafts at a point where the caving has not injured them. Most of the work is now done from shafts Nos. 3 and 5. The method of mining is the caving system, slightly different in the newer workings—that is, in the lower levels—from what it is higher up. The following concise description by Denton will give an idea of the system:[a]

Down to the eighth level the method of mining is as follows: Main levels are driven 75 feet apart and generally there are two main drifts at the bottom of each block, running approximately parallel on opposite sides of the block of ore. From these main drifts raises are put up at intervals of about 50 feet, and from these raises four series of subdrifts are run. The sets in the main drifts are made of 9-foot caps and 7-foot legs, and those in the "subs" of 6-foot caps and 6-foot legs. This leaves about 8 feet of ore between the sublevels. The sets are placed 3 to 4 feet apart. As the raises are put up, sets are placed to start the first subdrifts; but these drifts are not run at once, but are omitted to strengthen the main drifts until the fourth, third, and second "subs" have been worked out. When the subdrifts are completed, the block of ore between any two levels is honeycombed with drifts with vertical intervals of 8 feet of ore. When mining above has been completed, the removal of the ore pillars on the top "subs" begins. The pillars are sliced away, the back is caved, and the caved ore is removed in wheelbarrows to the chutes leading to the main level below. The chutes are 4 feet square and lined with 2-inch plank placed on edge. When the sand or overlying timber appears, a new slice is taken off the pillar and the back of ore is caved, as before, until finally all of the subdrifts have been worked out, when the operation of caving is continued in the block below, which in the meantime will have been honeycombed by the first or preparatory subdrifts.

Below the eighth level the method of mining has been modified. What are called intermediate main drifts are driven through the ore at intervals of 20 feet

[a] Trans. Am. Inst. Min. Eng., Vol. XXI, 1892, p. 355.

SCRAMMERS IN MINE USING CAVING SYSTEM.

From photograph belonging to the Minnesota School of Mines.

instead of 75 feet, and no subdrifts are used. The intermediate main drifts are of the regular size, 9-foot caps and 7-foot legs, which leaves about 10 feet of ore to be caved, instead of 7 to 8, as before. Stations are made at the shaft for each intermediate main level. Under this modified system the removal of each 20-foot block will be done as before, but the putting up of raises will be saved, and it is intended to use cars and thus do away with wheelbarrows as far as possible.

Pl. X, *B*, shows a main drift which has begun to cave under the weight caused by the wrecking of the subdrifts just above. Pl. XI, shows the miners removing the ore from a part of the mine where the caving has taken place.

The ore mined by the Chandler is good hard hematite, practically as hard as the Soudan ore. Subsequent to its formation (p. 233) it was fractured by the orogenic forces which folded the rocks, and it was thereafter not completely cemented. A more complete healing of these fractures seems to have taken place in the ore exposed by the workings of the Savoy mine (old Section 26 mine), at the eastern end of the Ely trough. The caving system described above, as followed in the Chandler mine under Manager John Pengilly, takes advantage of the fracturing which already exists in the ore and carries it farther through the pressure of the superincumbent load. As a result, the mass of ore obtained in this way is very much brecciated, so that it can readily be broken up by picks. In consequence of the ease with which it can be obtained by picking, the ore is frequently erroneously spoken of as a soft ore. The individual pieces of the breccia, it must be borne in mind, are, however, the hard hematite, nearly as hard as that of the Soudan mines. In driving some of the headings, where the caving has not affected the ore, machine drills are very frequently employed.

PRODUCTION AND SHIPMENTS OF IRON ORE FROM THE VERMILION DISTRICT.

The following tabulated statement gives the annual production and shipments of iron ore for the Vermilion district and the totals for the district since the date of the first shipment (1884) up to the present. The figures for the annual production during the early years of the mines were not obtainable, but have been given as a lump sum for those years. The figures have been compiled by the Minnesota Iron Company, and are the most accurate that can be obtained.

Statement showing production and shipments from all Vermilion Range mines since 1884.

Year.	Minnesota or Soudan.		Chandler.	
	Production.	Shipments.	Production.	Shipments.
	Long tons.	*Long tons.*	*Long tons.*	*Long tons.*
1884		62, 122	----------	----------
1885	1, 182, 882	227, 075	----------	----------
1886		307, 949	----------	----------
1887		394, 911	----------	----------
1888	312, 088	454, 019	169, 457	54, 612
1889	553, 172	479, 240	317, 827	306, 220
1890	518, 600	540, 013	364, 659	336, 002
1891	513, 667	508, 842	469, 741	373, 403
1892	568, 471	498, 353	718, 014	651, 799
1893	429, 170	485, 778	427, 595	435, 379
1894	448, 943	391, 612	588, 475	562, 088
1895	412, 636	431, 647	347, 449	600, 987
1896	427, 797	448, 970	551, 310	471, 544
1897	502, 738	592, 244	586, 353	438, 366
1898	426, 240	428, 054	628, 268	716, 049
1899	441, 000	456, 225	648, 296	808, 324
1900	310, 000	325, 025	644, 053	644, 801
1901	257, 677	208, 284	659, 820	627, 379
1902	307, 166	275, 168	593, 750	645, 575
Totals	7, 612, 247	7, 515, 531	7, 715, 067	7, 672, 528

Year.	Pioneer.		Zenith.		Savoy and Sibley.	
	Production.	Shipments.	Production.	Shipments.	Production.	Shipments.
	Long tons.	*Long tons.*	*Long tons.*	*Long tons.*	*Long tons.*	*Long tons.*
1884	----------	----------	----------	----------	----------	----------
1885	----------	----------	----------	----------	----------	----------
1886	----------	----------	----------	----------	----------	----------
1887	----------	----------	----------	----------	----------	----------
1888	----------	----------	----------	----------	----------	----------
1889		3, 144	----------	----------	----------	----------
1890		12, 012	----------	----------	----------	----------
1891		3, 079	----------	----------	----------	----------
1892		2, 651		14, 991	----------	----------
1893	540, 299	----------		14, 388	----------	----------
1894		----------	97, 961	----------	----------	----------
1895		40, 054		----------	----------	----------
1896		149, 073		18, 765	----------	----------
1897		207, 103		40, 817	[a] 29, 408	----------

[a] In stock.

Statement showing production and shipments from all Vermilion Range mines since 1884—Continued.

Year.	Pioneer.		Zenith.		Savoy and Sibley.	
	Production.	Shipments.	Production.	Shipments.	Production.	Shipments.
	Long tons.	*Long tons.*	*Long tons.*	*Long tons.*	*Long tons.*	*Long tons.*
1898	30, 740	123, 183	3, 924	....	42	....
1899	381, 304	339, 897	76, 303	79, 322	97, 081	86, 191
1900	492, 393	450, 794	54, 252	60, 089	175, 251	175, 118
1901	620, 659	678, 301	73, 512	60, 037	194, 329	211, 799
1902	669, 745	673, 863	162, 006	167, 206	324, 865	321, 054
Totals	2, 735, 140	2, 683, 154	467, 958	455, 615	820, 976	794, 162

	Long tons.
Total production	19,351,388
Total shipments	19,120,990

PROSPECTING.

From the facts of occurrence given in the preceding pages we are enabled to draw the following conclusions concerning the localities at which prospecting for ore might be advantageously prosecuted in the Vermilion district At the outset it may be said that as a result of the mode of formation and occurrence of the ores it is very probable that all of the large ore deposits which exist will somewhere reach the top of the iron formation. However, in consequence of the glacial drift which covers a large portion of this region, the ore deposits rarely reach the present surface of the ground, being buried by the drift. In the case of the deposits at Tower and Soudan, the ore, on account of its exceptional hardness, outcropped upon the tops of the highest hills, which, owing to their height, are, to a very considerable extent, free from the drift. But usually the ore is softer than the adjacent hard jasper and chert and greenstones, and is likely to have suffered more from erosion than these. Hence the ores commonly occupy more or less marked topographic depressions.

At Ely the exposures were first found at the west end of a broad basin, illustrating what the writer considers the typical occurrence, at least for the east end of the district. Since igneous rocks form the impervious basements upon which the ore deposits rest, it follows that the igneous rocks should be examined with great care, especially where they are impregnated with iron and are in the condition in which they are known as the paint rock. The ideal condition for the accumulation of ore is, as has been shown, a pitching trough of greenstone, with a great thickness of fractured jasper lying in it. The most favorable conditions for the formation of an ore body or ore bodies of some size are present where there is an amphitheater of greenstone within which lies the jasper, in a much crumpled and fractured condition, with the axes of the synclines plunging toward the opening of the amphitheater of greenstone. Unfortunately, even when these favorable conditions are found, only exceptionally has the accumulation of the ore taken place.

The size of the ore bodies varies much as the result of a number of factors, but one can state with confidence that the larger the amphitheater and the larger and thicker the mass of iron formation, and the fewer the dikes contained within this formation—whose effect would be to subdivide the large pocket into a number of smaller ones—the more likely will an ore deposit found prove to be a large one.

The Tower and Soudan deposits are in synclines which occur on the top of anticlines, forming hills. As the result of this known occurrence, the prospectors have appeared very generally to neglect explorations in low ground. But there are a number of areas of low ground that are with great degree of probability underlain by the iron formation, and some of them possibly by iron ore, which should be explored, for, as already noted, where the ore is soft it is generally found to occupy the lower areas. The difficulties attending prospecting in these low areas are great, on account of the water and the deep drift frequently found in them; but they may contain ore deposits which will pay in proportion to the difficulties attendant upon their discovery. It may be well to call to mind the fact that some of the large deposits occurring in Michigan—for instance, the Aragon mine of the Menominee range and the Lake Angeline of the Marquette range—are found in such positions.

But it should be emphasized that, as a matter of experience, no large ore deposits have been found except where the iron-bearing formation has considerable breadth. At many points the favorable conditions mentioned above, except the presence of broad bands of the iron-bearing formation, have been found; but in no known case where the iron formation is narrow have such localities yielded workable ore deposits. Certainly experience in the Vermilion district does not justify the expenditure of money in exploring the narrow bands of jasper. Many thousands, probably hundreds of thousands, of dollars have been spent in exploring these narrow bands without any returns.

A close study of the map shows some places which seem favorable for prospecting. In a general survey it is impossible to study a district in such detail as to warrant an expression of opinion as to individual localities. In fact, such very detailed study with a view of determining the exact location of ore deposits can hardly be considered a part of the functions of a national survey.

The exploration of the iron-bearing formation as an economic problem should be handled by the mining companies. They would unquestionably find it greatly to their advantage to have competent geologists make exceedingly detailed surveys of properties in which there are large belts of the iron formation. If such surveys show that certain areas have conditions favorable for ore deposits it would be advisable to burn over such areas so as to increase the number of exposures, and thereby make the areas more accessible. Finally the favorable locations should be narrowed down still more by careful dip and horizontal magnetic-needle observations. Only when all this preliminary work is done should a decision be made in reference to underground work.

The cost of such preliminary surveys as are advocated is insignificant when compared with the money required for diamond drilling and other underground work. Many such expenditures in the past would not have been made had the results of the surveys advocated been available. Apropos of the cost of the diamond-drill work, it may be stated that, from information derived from various sources, the estimate has been made that one of the old companies operating in the Vermilion district expended at least $1,000,000 in exploratory work without having uncovered thereby any body of ore of size sufficient to warrant its exploitation. The preliminary expenditure of a very small fraction of this amount of money for good surveys in advance of underground work would have made unnecessary the expenditure of much of it, and perhaps would have rendered the expenditure of a part fruitful.

In conclusion, it may be recalled that the only productive mines are at two localities, one on the belt of iron formation near Tower and Soudan, and the other on the belt of iron formation running east from Ely. Notwithstanding extensive but more or less haphazard exploration of other large belts for many years, no additional deposits have yet been developed. However, it is by no means proved that some of these belts may not yield runs of ore. But the iron-bearing formation and the Ely greenstone are so intimately mixed that some of the belts which seem to be largely iron formation may be really to a very large extent composed of greenstone and jasper. Under these conditions, the systematic exploration of even those belts which appear to be the most promising is a matter of extraordinary difficulty. Certainly the Vermilion district is the most difficult to explore of any of the iron-bearing districts within that part of the Lake Superior region in the United States.

SECTION IV.—GRANITES.

GENERAL STATEMENT.

At a great number of places throughout the Vermilion district acid rocks of various kinds have been found. Their macroscopic and microscopic features demonstrate their igneous character without possibility of question, and their relations to the adjacent rocks give further proof of this, as they are found cutting through both the Ely greenstones and the iron-bearing Soudan formation of the Archean. These rocks vary from fine- to coarse-grained granites and from porphyries with very fine-grained groundmass to granite-porphyries. The normal granites predominate. They are known from the topographic features with which they are associated as: (1) The granites of Vermilion Lake; (2) the granites of Trout, Burntside, and Basswood lakes; (3) the granite between Moose Lake and Kawishiwi River; (4) the granite of Saganaga Lake. These granites will be considered in detail in this section.

THE AGE OF THE ACID INTRUSIVES.

All of these rocks are younger than the Ely greenstone, for they occur in it as dikes. A number of the dikes are also found in the Soudan formation, which is itself of more recent origin than the greater part of the Ely greenstone. That these intrusives are older than the next sedimentary formation of the district—the Ogishke conglomerate, of Lower Huronian age, which succeeds the Soudan formation—is shown positively by the fact that they occur as pebbles in this conglomerate, and that their detritus largely constitutes the rocks of this formation. Speaking broadly, the general period of intrusion of all of these acid igneous rocks may be placed between the period of the deposition of the latest sediments of the Archean and that of the deposition of the earliest sediments of the Lower Huronian series. Some were intruded near the beginning of this interval, others probably near the end, but it is now impossible to give their exact ages. In the description of the rock from each of the large areas after which it is named an attempt will be made, where there are any facts which warrant this, to determine more closely its period of intrusion relative to the other igneous rocks as well as to the sediments.

GRANITE OF VERMILION LAKE.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Distribution.—Granites and related acid rocks are found in great quantity on the islands in Vermilion Lake and on the adjacent shores. They are not, however, confined in their distribution to the immediate vicinity of the lake, for scattered dikes of similar rocks are found cutting through the various older formations in places many miles distant from Vermilion Lake. Direct surface connection of these distant dikes with the main masses can not of course be shown, but from their similarity to the larger masses in the area it is presumed that both are derived from the same deep-seated source.

Exposures.—The exposures of these acid rocks are very numerous, and many of them afford opportunity for a study of their different kinds, but they rarely show more than a single contact when the contact is between members of the same eruptive series, so that in most cases it is impossible to tell the exact relations of these rocks to one another—that is, to determine which is of younger age. Some of the best places at which to see these Vermilion Lake intrusives are the east end of Ely Island, the point south of Mud Creek Bay, Stuntz Island, the conical island east of Stuntz, the prominent point of land farther east of this conical island, and the high, bare hills on the north side of the "Burnt Forties." Dikes of these rocks are also numerous in the Ely greenstone north of Mud Creek Bay, where one of them about 30 feet wide, cutting the greenstone and trending east and west, can readily be seen from the water's edge as a white streak along the hillside.

On the flanks of knolls occupied by the igneous rocks we very commonly find sedimentary rocks—conglomerates and graywackes—which have been derived from them. In many cases, moreover, it is only after very careful and patient examination that the igneous rocks can be separated from the derived sedimentaries, for where the constituents of these derivative rocks have been merely cemented together without having been much rolled and rounded, and where the deposits are not well stratified, the resemblance between the true igneous rocks and the rocks derived from them is very great indeed.

The igneous rocks that occur at a considerable distance from the lake are exposed over only very small areas. In some cases the exposure is sufficient to show that the rocks are dikes in older rocks, and very commonly this relation is inferred from the occurrence of these rocks in the midst of numerous exposures of rocks belonging to formations which, from facts observed in other localities, are known to be of greater age than the eruptives.

Topography.—The eruptives usually occupy the crests of hills, or occur in rounded or oval hills higher than those occupied by the surrounding rocks. They thus are seen to influence the topography to a considerable extent. This influence is, of course, best shown in those areas where the rocks occur in large quantity, as, for example, the islands in Vermilion Lake and the lake shores, rather than at places some distance away, where they occur as very small masses.

PETROGRAPHIC CHARACTERS.

The rocks considered in this section form a complex varying in both macroscopic and microscopic characters, as well as in chemical composition, yet in spite of these variations their close field relations and their characters as determined by laboratory study show that they all belong to one petrographic province and that they were formed at the same geologic period.

All of the rocks belonging to this series of eruptives are very light colored, at the most showing slaty-gray to greenish-gray colors upon fresh fracture. On weathered surfaces they are usually white or light gray, varying to yellowish or pinkish.

Macroscopic characters.—The rocks under discussion vary from fine-grained granites to those of coarse grain, and from porphyries with felsitic groundmass and rare phenocrysts to coarse-grained granite-porphyries.

The porphyritic rocks are most common. Quartz is the usual phenocryst, but it is sometimes accompanied by feldspar. In some of the porphyries the phenocrysts are very abundant, but in others they are very scarce. The quartz phenocrysts range in size from those that are scarcely separable from the quartz of the groundmass up to crystals nearly an inch in diameter. Two characteristic porphyries especially are of common occurrence in the district. One contains a great number of small vitreous-looking quartz phenocrysts; the other usually shows only a few very large phenocrysts. The quartz phenocrysts differ greatly in number in different types of the rock. In some of the rocks only a few are present; in others they occur in great abundance. Moreover, the quartz shows considerable variation in character. Usually it is clear and vitreous; less commonly it has a somewhat bluish tinge, but is still vitreous. Very commonly white, opaque, porcelain-like phenocrysts appear, and some are found that are black and opaque. Usually the quartz phenocrysts of the rock occurring at a single exposure are all alike; that is, all are clear and colorless or all are black, but sometimes these are found intermingled.

Feldspar in white crystals appears also as phenocrysts in the porphyries and, like the quartz, varies much in abundance. The dark phenocrysts seen in these rocks are either mica or hornblende, or occasionally the two together, but as a rule dark phenocrysts are scarce.

The groundmass of these porphyries gives to them some of their distinctive characters. In some the groundmass is dense and aphanitic; in others it is distinctly granular; in still others it is coarse grained; moreover, there are phases of the groundmass that show all gradations between these different kinds. In some of the porphyries, as has been said, the phenocrysts are practically wanting, and as these become reduced in quantity the rocks gradually change to those which we would call granites; and we find not only changes from porphyries into granites, but gradational phases among the granites, varying from fine-grained microgranites to normal coarse-grained granites.

The granites and porphyries of Vermilion Lake occasionally include fragments of the iron-bearing Soudan formation, both large and small, as well as fragments of greenstones, but they contain no inclusions of a recognizably sedimentary rock other than those derived from the iron-bearing formation.

Microscopic characters.—The result of microscopic examination sustains the determinations made by macroscopic studies. It shows that there are present in the acid intrusives of Vermilion Lake the following petrographic varieties: Rhyolite-porphyry, feldspathic porphyry, microgranite, granite, microgranite-porphyry, and granite-porphyry. The minerals occurring in all of these are essentially the same. Under the microscope quartz is the most prominent primary constituent, and ranges from minute particles taking part in the construction of the groundmass up to phenocrysts an inch in length. Both orthoclase and plagioclase feldspar occur in the groundmass and as phenocrysts. Polysynthetically twinned plagioclase predominates among the phenocrysts. These feldspars are much altered and an accurate determination of their characters was not made. Brown mica occurs occasionally as phenocrysts and is almost always altered to chlorite. A few individuals of common green hornblende were observed, which appear to be primary. Apatite, sphene, zircon, and a little iron oxide were also observed. From these various minerals there have been produced by alteration the following secondary minerals: Calcite, which is distinctly ferriferous, chlorite, epidote, zoisite, sericite, muscovite, and rutile. Pyrite in cubes is also commonly found in some of the altered intrusives. The texture of these rocks is normally granitic, although occasionally a tendency to a trachytic texture was observed in some of the porphyries and more commonly a micropegmatitic texture was seen.

No analyses of these intrusive rocks have been obtained. Indeed no special effort has been made to obtain analyses, for the reason that their field associations and general characters show clearly that the various kinds of rock included under the above head belong genetically together, and for the further reason that the rocks are without exception considerably altered, so that analyses might be misleading rather than helpful. It is highly probable that analyses of fresh rocks, could such be obtained, would show that these acid intrusives range from the granites toward the diorites by increase in soda-lime-feldspar and diminution in quartz and orthoclase, as is indicated in some of the feldspathic porphyries.

FOLDING.

These intrusives have been subjected to dynamic action, for they are very commonly jointed, and in some places even rendered schistose. They have also taken part in the folding, but owing to their general homogeneous nature it is impossible on exposures consisting of intrusive rocks alone to trace out the extent and character of this folding. Where the intrusives are associated with younger sedimentary rocks the folding is clearly shown, and is described on pages 288–291.

STRUCTURAL FEATURES AND METAMORPHISM.

As a rule the intrusives are broken up by a series of joints, which are sometimes so close together that the rocks break up into small more or less regular rhombs. The very general distribution of the jointing seems to point to the fact that the rocks were not buried very deep, for had they been so buried it is probable that they would have acted more as viscous materials, and that schistosity would have been developed, instead of the stress being relieved by the formation of joints, as is the case. As a rule, however, the rocks composing the blocks between the fractures show no or very slight indications of schistosity. On these jointed rocks it is not uncommon to find a few shearing planes along which schistosity has been developed. Moreover, the rock is sometimes schistose along the small fracture planes themselves. Reference has casually been made to the difficulty sometimes experienced, even under favorable circumstances, of distinguishing between these igneous intrusives and some of the sedimentary rocks derived directly from them. When schistosity has been developed in the igneous rock, even though it be imperfectly developed, the difficulty is much increased, whether the test applied be that of macroscopic or microscopic examination, or, as in most cases, the two combined.

Some very interesting occurrences of pseudo-conglomeratic rocks derived from these acid rocks by orogenic movement may be seen at Vermilion Lake. One of the best cases is shown on the flat island lying just south of Ely Island, in the NE. $\frac{1}{4}$ of the NE. $\frac{1}{4}$ of sec. 30, T. 62 N., R. 15 W. This island is composed chiefly of rhyolite-porphyry, with fine felsitic groundmass, having large quartz phenocrysts scattered through it. This porphyry is intersected by two sets of partings, which vary from big joints down to very minute parting planes. One of these sets of fractures strikes N. 15° E. and the other N. 80° W. These planes of fracture separate the rock into numberless more or less regular rhombs. The large joints, a foot or more distant from one another, break the rock into large rhombs, which in their turn are subdivided into a great number of smaller ones by systems of still smaller joints and parting planes having the same trend as the larger fractures. After the formation of the joints movement took place along the fracture planes, and as a result of this movement the rhombs have been rubbed against one another and their angles have been more or less completely rounded, so that the rhombs have acquired now a more or less perfect oval outline. The long axes of the ovals agree, of course, since the ovals were all produced by the same processes. The rock is now strikingly like a conglomerate, and forms a fine example of a pseudo-conglomerate. This pseudo-conglomerate may, nevertheless, readily be distinguished from true conglomerates, such as occur in abundant typical development at Vermilion Lake, and especially on the shores of Stuntz Bay, by the fact that all of the pebbles of the pseudo-conglomerate are of exactly the same kind of porphyry, and that the matrix between the pebbles is merely a sheared form of the same porphyry. Moreover, no indication of bedding whatsoever is found in this pseudo-conglomerate. The true conglomerates contain pebbles of various porphyries, as well as of the older greenstone and the iron-bearing formation, and gradations can be followed from these conglomerates into the graywackes, and through these into the overlying slates. The pseudo-conglomerate is most typically developed at the location given above. It is seen in less typical development on the point south of Mud Creek Bay and at some other localities on Vermilion Lake. It is not so common, however, as one might be led to suppose from previous descriptions of the Vermilion district.[a] Far more numerous are the exposures of the porphyry on which the fracturing is not very distinct, and on which movement has not been sufficient to produce the rounding of the rhombs and the pseudo-conglomeratic structure. These pseudo-conglomerates were described by Smyth and Finlay[b] under the name "conglomerate breccias," and the manner in which they were formed was correctly interpreted. However, these authors unfortunately classed in their conglomerate breccias the enormously and typically developed sedimentary conglomerates that occur on the islands and shores at the east and southeast side of Vermilion Lake, and in particular on Stuntz Bay of that lake, where they are interbedded with and grade into the normal finer-grained graywackes and slates.

---

[a] The geological structure of the western part of the Vermilion Range, Minnesota, by H. L. Smyth, and J. Ralph Finlay: Trans. Am. Inst. Min. Eng., Vol. XXV, 1895, pp. 610–613.

[b] Op. cit., pp. 629–633.

Sericite-schists.—When the crushing and accompanying alteration are considerably advanced, sericite-schists are produced from these porphyries and granites. At one stage we find a few eyes of quartz and feldspar left. These lie in a finely granular groundmass in which the parallel structure of the secondary minerals is very evident. This parallelism is most pronounced when the rock contains a great deal of sericite, for then the plates of sericite are arranged parallel to one another and greatly emphasize the structure. The parallel arrangement follows around the phenocrysts, showing that it was produced after their formation. It may be that in some cases this parallelism represents partly an original flow structure which has been emphasized by the production of the secondary minerals. The extreme stage shows a very fine-grained schistose rock which is of a yellowish-green color macroscopically, and which under the microscope is seen to be a finely granular aggregate of quartz, presumably some feldspar, and flakes of sericite, these being the predominant minerals.

Chlorite-schists.—In a number of cases the porphyries show abnormal alteration to a green chlorite-schist instead of to a sericite-schist. Such alteration was found in immediate association with the iron-bearing formation—that is, where the acid rocks had been intruded and then infolded in the iron formation. The production of the chlorite and of the green color in general is due to the infiltration of iron from adjacent formations. In some instances the green coloration is found only along the contact of an acid dike with the iron formation and extends only a few inches into the porphyry. In other cases, where the acid rock is in the midst of the iron formation, the rock is distinctly green, and might be, and in fact has been taken for a product derived from the altered basic rocks of the area—the greenstones. In some places the quartz phenocrysts have been granulated, but in others they are still intact and show clearly the fact that these schists were derived from acid rocks. The effect of the iron in causing the production of chlorite instead of sericite can be seen in many places in the massive acid rocks. In these we very commonly find that when iron pyrites occurs it is almost invariably surrounded by a zone of limonite of variable thickness, and beyond this zone of limonite there is a chloritic zone in the groundmass, whereas elsewhere sericite occurs and not chlorite.

Schistose granites and schists derived from granites.—Locally these granites have been very much crushed, and as a result of this crushing there has been developed in a number of cases a parallelism of the feldspar and quartz and, especially, of the mica and secondary chlorite. The quartz shows clearly the effects of the crushing in the very common undulatory extinction, in the fractures that pierce the phenocrysts, and in the granulation of the phenocrysts, which represents the final stage. This crushing has, of course, more or less completely obliterated the textures and has usually greatly altered the minerals. Fractures passing through rocks have been healed by infiltrated quartz, or by secondary feldspar in cases where the fractures cross the feldspar phenocrysts. In such a case the secondary feldspar corresponds in extinction with the adjacent feldspar bordering the fracture, but is fresh and clear, and is readily distinguishable by these characters from the altered original feldspar.

RELATIONS TO ADJACENT FORMATIONS.

The acid rocks described above are younger than the adjacent Ely greenstones and Soudan formation. They occur in dikes in both of these formations and include fragments of both. Detailed descriptions of the occurrences of some of these rocks will be found under the heading "Interesting localities" (p. 255).

Relations to Lower Huronian series.—The relations of the granite of Vermilion Lake to the Lower Huronian sediments will be discussed in detail later. It will suffice here to state that these sediments have been derived partly from the acid rocks and hence are younger than they. The detailed proof of their relations will be given in the chapter devoted to the discussion of these sediments.

Interrelation of granites of Vermilion Lake.—The acid intrusives, while of the same general age with respect to the older and younger sedimentary formations, show certain age relations among themselves which are interesting. The fine granite seems to be rather more extensively developed, on the whole, than the rhyolite-porphyries and the granite-porphyries. This granite is cut at several points by dikes of fine-grained granite-porphyry containing small quartz phenocrysts—for instance, on the point south of Mud Creek Bay, on Stuntz Island, on the island just west of Stuntz Island, and at a locality just north of the prominent jasper outcrop on the east side of Stuntz Bay. This granite-porphyry is in its turn found to be intruded by the granite-porphyry containing the large quartz eyes.

Such an occurrence was observed in the Burnt Forties, for example. Thus the succession, beginning with the oldest of the intrusives, is: Fine- to medium-grained granite, fine-grained granite-porphyry with small eyes, and coarse granite-porphyry with large quartz eyes. The relation of the rhyolite-porphyry to the other acid eruptives is not definitely known, as no occurrence has been found in which the relations between them are shown.

INTERESTING LOCALITIES.

Localities showing relation between granite of Vermilion Lake and the Ely greenstone.—The relations between the acid intrusives and the Ely greenstone are clearly shown at many places in the Tower area of the Vermilion district. In the following paragraphs some of the most accessible of these places will be mentioned.

On the north shore of Mud Creek Bay, in sec. 1, T. 62 N., R. 15 W., immediately north of the westernmost island in this bay, there is a broad dike of nearly white medium-grained porphyry which trends east and west, and can be distinctly seen from the water. This dike cuts directly across the Ely greenstone, showing sharp contacts with it in many places.

Just northeast of this place, on the section line between sec. 1, T. 62 N., R. 15 W., and sec. 6, T. 62 N., R. 14 W., are dikes of granite cutting the greenstone and the iron formation infolded in the greenstone. In fact, one can hardly go a quarter of a mile in any direction over these nearly bare hills without finding one or more of these acid dikes. The greenstone is in many places schistose, and the dikes are also frequently found to be more or less schistose along their margins, the schistosity striking a little north of west. The presence of this schistosity is clear proof that the area has been folded subsequent to the period of the intrusion of these igneous rocks.

About the center of sec. 6, T. 62 N., R. 14 W., there is a large boss of porphyritic granite, which is completely surrounded by more or less schistose greenstone. Numerous dikes of granite, ranging from a few inches up to 15 feet in width, and perfectly massive, evidently offshoots from this central boss, penetrate the greenstones. Frequently they follow the schistosity, but in some cases they cut across the schistosity, and in places they include fragments of the schist. Since the position of these intrusives has evidently been influenced by the preexisting schistosity, they were evidently intruded somewhat after those that have already been mentioned. They are believed, however, to belong to the same general period of intrusion.

On the hills south of Mud Creek Bay and south of Mud Creek itself there are also numbers of dikes of granite and porphyry which cut the ellipsoidal greenstone.

The following are other localities where the acid intrusives cutting the greenstone may be studied:

North 1,000 paces, west 1,000 paces, from southeast corner of sec. 9, T. 62 N., R. 14 W. Here a granite-porphyry containing large phenocrysts of quartz cuts through a dense greenstone forming the bluff overlooking the swamp to the south. A similar dike is to be found at north 1,650 paces, west 950 paces, from southeast corner of sec. 21, T. 62 N., R. 14 W.

West 1,000 paces, from southeast corner of sec. 10, T. 62 N., R. 14 W. Here the porphyry is fine grained, and has a dense groundmass.

North 200 paces, west 100 paces, from southeast corner of sec. 27, T. 62 N., R. 14 W. This is one of the feldspathic porphyries.

Relations of the acid intrusives to the Soudan formation.—On the bold, bare hills of jasper, at a point north 270 paces, west 200 paces, from the southeast corner of sec. 7, T. 62 N., R. 15 W., a dike of granite-porphyry 20 paces wide, containing large phenocrysts of quartz, cuts through the jasper. It cuts across the strike of the bands of jasper in places and runs out into the jasper in small stringers, and also includes fragments of the jasper. The grain of the intrusive rock is seen to be noticeably finer along the contact of the small stringers than it is in the main mass of the granite. Reference has already been made to the granite dikes found cutting the jasper in sec. 1, T. 62 N., R. 15 W. In both of these places the relations are perfectly clear.

Contacts between these two kinds of rock were not found at many places, but where they were observed the relationship was clearly shown. At 1,125 paces north, 1,300 paces west, of the southeast corner of sec. 20, T. 62 N., R. 14 W., a dike of feldspar porphyry cuts through the jasper and the associated green schist. This porphyry includes large fragments of the jasper and small ones of the green schist, showing conclusively its relations to them. In places these fragments are so numerous that the rock distantly resembles a conglomerate.

Relations of the different varieties of the acid intrusives of Vermilion Lake to one another.—On the bare ridge south of Mud Creek Bay the granite-porphyry is found cutting the feldspathic porphyry at several places. One such dike may be found about north 700 paces, west 1,400 paces, from the southeast corner of sec. 7, T. 62 N., R. 14 W. Again, on the high hill in the Burnt Forties overlooking the lake the granite-porphyry is found in contact with, and apparently cutting, the fine-grained porphyritic granite, and includes fragments of greenstone and jasper. It is interesting to note that immediately around these jasper inclusions the acid intrusive has become green as the result of the infiltration of iron and the production of secondary chlorite instead of sericite. From this green background the phenocrysts of quartz stand out very prominently. A similar alteration occurs in the acid sills that were intruded through the iron formation on Soudan Hill.

East of Stuntz Island there is a conical island which is made up chiefly of the fine-grained feldspathic porphyry, and on which there is a dike of porphyritic granite, about 25 paces in width, running from northwest to southeast. At certain places in this dike, especially on the southeast slope of the island, the granite grades into a rock corresponding very closely to the coarse-grained granite-porphyry. On the other hand, at other localities, the same porphyritic granite was observed to pass into a form of rock very similar to some of the phases of the feldspathic porphyry. It would appear from this that these different kinds of rock were all derived from the same source, and that they merely represent different phases of development of essentially the same magma. Upon this conical island there were noted also several small dikes of green schistose basic rock, one of them running nearly east and west and having a width of from 8 to 12 inches.

On Stuntz Island itself, especially upon the northwest arm of the island, a mass of this porphyritic granite was found trending about east and west, cutting through the feldspathic porphyry.

Nearly all of these porphyries contain more or less oval yellowish-green fragments of rock which apparently were derived from the greenstone through which they were intruded.

GRANITES OF TROUT, BURNTSIDE, AND BASSWOOD LAKES.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Distribution.—The rocks described under the above heading occur along the northern edge of the Vermilion district, and extend from Vermilion Lake on the west to the east side of Basswood Lake on the east, where they cross the international boundary. Observations made on Hunters Island, Province of Ontario, Canada, show that similar rocks are present in that province and that they possess the same geographic and geologic relationship to the members of the Kaministiquia iron range, which is the continuation of the Vermilion iron range of Minnesota to the northeast, as do their Minnesota analogues to the various members of the Vermilion iron range of Minnesota. They are for this reason presumed to belong geologically with the granite of Basswood Lake. While it is known that the granites of Trout, Burntside, and Basswood lakes extend at least as far northeast-southwest as the limits of the area mapped, these granites—or granite closely related to them—are presumed to have a very much greater areal extent, as upon the Canadian maps granites are shown covering large areas in portions of Ontario which are continuous with the Vermilion range. The Minnesota and Canadian maps and a traverse made by canoe show that granite extends a considerable distance north of the international boundary. Since the prime object of the survey whose results are here described was to study the Vermilion district from an economic point of view, no attempt has been made to study the outlying granite more closely than was requisite to determine its relations to the rocks of the district. Moreover, observations have been confined almost altogether to a very narrow area bordering the main mass of granite. The traverses usually ended as soon as we were sure that the limits of the granite had been passed.

Exposures.—The exposures are, as a rule, very numerous, and the line of contact between the main granite area and the area of the Vermilion range proper is usually marked by a topographic break of some kind. Either a valley and stream are present or else a lake or chain of lakes lies along the contact. In either case as soon as the depression is crossed, if one comes from the south, for instance, the granite exposures usually begin, and they continue in great number as far north as we have been.

Topography.—The granite does not seem to affect the topography very materially. One point noted is that the lakes in the area of the sediments have, as a rule, a northeast-southwest trend, agreeing thus with the structure of the district, upon which they are largely dependent, whereas in the granite area they are more likely to be of very irregular or more or less rounded outline, owing to the more homogeneous character of the granites by which they are surrounded. The hills in the granite area are usually rounded as a result of river erosion and subsequent glacial action. In detail the topography is very rough, as is that of all this portion of the country, but there are no very great differences in elevation. The district underlain by the granite does not in general seem to have been much more strongly affected by erosion than the adjacent portions of the Vermilion district. In the course of a reconnaissance it was observed that on the southeast side of Iron Lake, which is on the international boundary, just west of Crooked Lake, there is an area of country that has been reduced almost to a base-leveled plain, with Iron Lake as the plane of base-level. The shores of the lake for a considerable distance back from the water's edge possess all the features of such a base-leveled plain. The streams enter the lake through broad marshes having wide estuaries and flow in meandering courses through these marshes. An occasional hill (monadnock) of granite projects above this level plain. Some of the islands in the lake and points projecting into it are so low that in many places by rising in the canoe one can see over them.

PETROGRAPHIC CHARACTERS.

Macroscopic characters.—The granite of Trout, Burntside, and Basswood lakes shows a considerable variation in character, as one might be led to expect from its great areal distribution. In color it varies from very light gray through pink and reddish facies to very dark gray. An equal variation in grain may be seen. It ranges from very fine-grained to coarse-grained forms and also to granite-porphyries. The structure of the rock is in general massive, but with these massive forms occur gneissoid rocks varying in color from light gray to very dark. Some of these gneissoid rocks presumably owe their structure to pressure applied subsequent to their consolidation. In these the minerals show to a large degree the effects of pressure. Other facies may be due to differentiation processes and to movements in the unconsolidated magma. Between rocks formed in this way and those formed as the result of pressure, but in which complete recrystallization has taken place, no distinction can be made. In the areas examined the massive granites predominate greatly over the schistose rocks. In the following brief description only the massive granites will be considered.

Microscopic characters.—The mineral constituents are green hornblende, biotite, orthoclase, quartz, and plagioclase, with accessory sphene, zircon, and iron oxide. These minerals have been very much altered, so that their places are taken largely by secondary minerals, of which chlorite is the most prominent, and, after this, epidote and sericite and secondary feldspar. There is a variation in the mineral character, hornblende being practically wanting in some specimens and increasing very much in quantity in others. No cases were found in which the quartz was wanting, but it was reduced in quantity in some cases. The Trout, Basswood, and Burntside lakes acid rocks seem to vary from hornblende- and mica-granites to syenites, with the granites predominant.

RELATIONS TO ADJACENT FORMATIONS.

Relations to Ely greenstone.—In approaching that portion of the district in which the granite of Trout, Burntside, and Basswood lakes is exposed we cross over a broad area underlain by the Ely greenstone in its typical development, in which only rarely is a granite dike to be seen. The closer we get to the contact between the two above-mentioned formations the more numerous, however, become these granite dikes, until in places they are so common that we may almost consider the greenstone as having been thoroughly permeated by the granite magma. This intimate relationship is beautifully shown on the numerous exposures at the west end of Burntside Lake. It should be stated in this connection that the granite dikes cutting through the rocks exposed on the shores of this lake do not all belong to exactly the same period of intrusion, but show some slight differences in age. These differences are not, however, thought to be great. In other words, all of the granites are believed to belong to essentially the same period of intrusion.

From the intrusive relations above illustrated it is clear that the granite is younger than the adjacent greenstone. This intrusive relation is further emphasized by the progressive metamorphism shown by the Ely greenstone as exposures closer and closer to the main granite mass are examined, as described and explained on p. 156 et seq. It is not uncommonly found that the greenstone is schistose, and the granite dikes are seen to follow the schistosity, proving its development prior to the intrusion of the granite. The granite also includes fragments of schistose greenstone.

Relations to other intrusive rocks.—As stated above, the granite areas were not studied in great detail, but a sufficient number of observations were made to show that the granite is cut by both acid and basic dikes. The basic rocks are cut by acid dikes, as is shown in the photograph reproduced on Pl. XIII, *B*. The normal white to gray granite has been cut by a red-weathering granite which traverses it in dikes, but the period of intrusion of these later red granites has not been determined, even approximately.

AGE.

The granite of Trout, Burntside, and Basswood lakes is evidently younger than the Ely greenstone, which it cuts, includes, and metamorphoses. Dikes, offshoots from it, are found following the schistosity of the greenstone and including these schists. Hence it was certainly intruded subsequent to the formation of the schistosity in the greenstone. This schistosity was produced primarily as a result of the folding which took place subsequent to the deposition of the iron formation and which caused the folding of this iron formation. Therefore it is concluded that this granite is younger than the iron-bearing formation, although the jasper is in no place cut by dikes which can be connected directly with the main masses of the granite.

This granite is not clearly recognizable in the pebbles in the overlying Lower Huronian sedimentary series, but where this series comes closest to the granite its relations are sufficiently clear. Thus, for example, dikes of this granite, as in sec. 16, T. 64 N., R. 9 W., north of Moose Lake, are found to cut the greenstones underlying the sediments, but never to pass the contact and penetrate the sediments, although the dikes are numerous near the contact. Hence the conclusion is reached that the granite of Trout, Burntside, and Basswood lakes is older than the Lower Huronian sediments.

FOLDING.

If the granite has been subjected to severe mountain-making processes, as it presumably has, it does not now show any very marked effects of these. No folding, of course, could be traced in such a homogeneous rock, and it is only natural that one should find an occasional shearing plane along which the granite is more or less schistose. In general the granite, as already stated, possesses a very massive character. Unquestionably these rocks must have taken part in the folding of the district, but the presumption is that in general this great granite mass bordering the north side of the Vermilion district acted as a relatively unyielding area against which the rocks to the south have been forced. As a result partially of this, the adjacent greenstones, consisting primarily to a large extent of easily alterable pyroxene, have been metamorphosed into amphibolitic schists.

INTERESTING LOCALITIES.

In the following paragraphs will be found brief descriptions of some localities which show the relations of the granite of Trout, Basswood, and Burntside lakes to the Ely greenstone.

The relations between these rocks are very clearly shown at many places along the north and west shores of the northwest end of Pine Island and on the adjacent shore of the mainland, where granite dikes intrude the greenstone. These dikes are scattered over a wide zone along the contact between these two igneous rocks, and as a result of their intrusion the greenstone has been altered to amphibolitic schists. The dikes frequently contain large masses and smaller fragments of schists similar to those surrounding them. About 2 miles northeast of Mud Creek Bay and about three-fourths of a mile due north of the Sheridan mine, the schist is intricately intruded by the granite. The schist has been so broken up as the result of the intrusion that in places there has been formed almost an eruptive breccia, with the granite as the cementing material. In some cases the intrusive granite assumes roundish forms, and where the schist predominates one might almost consider the rock a pseudo-conglomerate with granite bowlders in a green schist matrix.

The relationship between the granite of Burntside Lake and the ellipsoidal greenstones is well shown at a great number of places on the shores of Burntside Lake. Coasting along the southern shore to the west of the portage one observes dikes of this granite in the ellipsoidal greenstone, which has been metamorphosed to an amphibolitic schist on the steep north-facing slopes in the southwest quarter of section 23. Similar exposures occur again on the point in the southwest quarter of section 22 and in the southeast quarter of section 21. The intrusive character of the granite and the intricacy of this intrusion is best shown on the almost continuous exposures that border the northwest shore of the lake in secs. 30 and 20, T. 63 N., R. 13 W. One starting at almost any place on the southern shore of Burntside Lake, where the granite dikes are numerous, will find that they diminish in number southward, and with this diminution in number at a distance from the main granite mass one will find that the schists gradually lose their schistosity and grade into the normal greenstones.

Two hundred paces north of the shore of Long Lake, on a line 1,000 paces west of the east line of sec. 21, T. 63 N., R. 12 W., there is a well-marked eruptive breccia, produced by the intrusion of granite of Burntside Lake, which includes a vast number of fragments of the greenstone forming the main country rock. A similar breccia is found about 70 paces farther north of the above location. A dike of the granite developed as granite-porphyry cuts the greenstone at 1,000 paces north, 1,000 paces west from the southeast corner of sec. 19, T. 64 N., R. 10 W.

The relationship between the granite of Basswood Lake and the Ely greenstone is well shown on a high hill at about 500 paces north of the southeast corner of sec. 17, T. 64 N., R. 9 W., and on the hill in the southeast quarter of sec. 16, T. 64 N., R. 9 W. At both of these places the greenstone is penetrated by numerous dikes, and it has been metamorphosed in most cases to amphibolitic and occasionally micaceous rock, in which schistosity is very frequently more or less well developed.

GRANITE BETWEEN MOOSE LAKE AND KAWISHIWI RIVER, IN SEC. 5, T. 63 N., R. 9 W.

DISTRIBUTION AND EXPOSURES.

Distribution.—In the SE. ¼ of sec. 5, T. 63 N., R. 9 W., there is an oval mass of granite, having diameters of about one-half mile northeast-southwest by one-fourth mile east-west. In the vicinity of this mass and in the greenstone area for several miles to the west—in general we may say in the territory between Moose Lake and Kawishiwi River—there are a number of granite and granite-porphyry dikes which, since they are of practically the same petrographic character as the large mass and show the same relationship to the adjacent rocks that this mass shows to similar rocks adjacent to it, are presumed to be offshoots from this large mass, or at least to have come from the same deep-seated mass of magma from which it came.

Exposures.—The exposures are fairly numerous where the large mass of granite occurs, but over a portion of the area underlain by this there is a large amount of fallen timber, which helps to conceal the rocks and renders the area exceedingly difficult of access.

PETROGRAPHIC CHARACTERS.

On fresh fracture this granite is dark gray in color, though at times it has a reddish tinge. On weathered surfaces it usually becomes grayish. It is of medium grain, and is sometimes developed as a granite-porphyry in which the feldspar and quartz phenocrysts can be easily seen lying in the dark-gray fine-grained groundmass. The granite-porphyry facies bears a very strong resemblance to the porphyries of Vermilion Lake, as well as to the porphyritic facies of the granite of Saganaga Lake. These rocks show only the ordinary characters of granites, and a brief description of them will suffice. The constituents are the usual ones—quartz, orthoclase, plagioclase feldspar so altered that no individuals suitable for close determinations of character could be found, a little brown mica, and magnetite. In the porphyry the feldspar is the most prominent phenocryst, occurring in both larger and more numerous individuals than the rounded quartz phenocrysts associated with it. The feldspar shows fairly good crystal contours, though sometimes the crystals are rounded. In the porphyries the groundmass in which the phenocrysts lie is a fine-grained aggregate of feldspar, quartz, calcite, epidote, zoisite, rutile, chlorite, biotite, sericite, and pyrite, all in small individuals. Most of these are of secondary origin, yet some of the quartz and feldspar, and possibly some of the biotite may be primary, although not recognizable as such.

RELATIONS TO ADJACENT FORMATIONS.

In immediate proximity to the main mass of this granite are the Ely greenstone of the Archean and sedimentaries of Lower Huronian age only.

Relation to Archean.—In the vicinity of the granite the Archean greenstone is cut by acid dikes which are petrographically similar to this granite and are believed to be offshoots from it. Hence the fact that the Ely greenstone is older than the granite is indisputably shown.

Although the Soudan formation does not occur near the main mass of the granite, nevertheless dikes similar to the granite are found cutting through this iron formation at places a number of miles distant from the main massive, and if it is admitted that these dikes belong to the same period of intrusion as the main mass of granite, then it is equally plain that the iron formation is older than the granite.

Relation to Lower Huronian.—The Lower Huronian sediments and the granite occur close to each other. For the most part these sediments are fine slates with graywackes and very few narrow bands of conglomerate. However, at a few places conglomerates have been found overlying and derived from the granite, and very good proof of the relations between the granite and Lower Huronian sediments is thereby given. Negative evidence is furthermore offered by the fact that no dikes which can be identified with the granite are found penetrating these Lower Huronian sediments, although they occur in the greenstones that immediately underlie these sediments, and are in close proximity to them.

Relation to Keweenawan.—The granite is itself cut by narrow dikes of coarse black diabase, which are supposed to be of Keweenawan age, the very youngest intrusives occurring in the district.

GRANITE OF SAGANAGA LAKE.

The granite of Saganaga Lake has probably one of the best-known names of any geologic formation occurring in the Vermilion district of Minnesota, for it has appeared repeatedly in the Minnesota reports and in other publications in which its field and age relations to the adjacent rocks have been discussed.[a]

---

[a] Winchell, A., Geol. and Nat. Hist. Survey of Minnesota, Sixteenth Ann. Rept., 1888, pp. 211–233 and 330–334. Grant, U. S., Geol. and Nat. Hist. Survey of Minnesota, Twentieth Ann. Rept., 1893, pp. 83–95; Final Rept., Vol. IV, 1899, pp. 321–323 and 467; also Am. Geologist, Vol. X, 1892, p. 7. Lawson, A. C., Am. Geologist, Vol. VII, 1891, p. 324. Geological age of the Saganaga granite, by H. V. Winchell: Am. Jour. Sci., 3d series, Vol. XLI, 1891, pp. 386–390.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Distribution.—This granite is confined in its occurrence to Saganaga Lake and its vicinity. It covers about 100 square miles in Minnesota, but only a portion of its area is shown on the accompanying map (Pl. II).

Exposures.—Within this area its exposures are very numerous, for the country is in many places comparatively bare of vegetation, the drift is as a rule thin, and the presence of large bodies of water—Saganaga, West Gull, and Red Rock lakes and their tributary streams—insure frequent exposures on the shore of the mainland and on the islands.

Topography.—The topography of this granite area offers a strong contrast to that of the surrounding country. In the surrounding territory, which is underlain by Archean greenstones and Lower Huronian sediments, the topography is rough, being marked by prominent hills, generally, to be sure, having the round contours characteristic of glaciated areas, but often presenting high and rugged cliffs. Within the granite area the topographic features are, for the most part, not strongly emphasized. The hills are low and rounded and the hilltops seem to approach very nearly the same level, so that in looking over this area from some of the higher surrounding elevations one gets an idea that this particular portion of the district has been reduced very nearly to a peneplain.

PETROGRAPHIC CHARACTERS.

Macroscopic characters.—This granite is very coarse grained over a large portion of the area in which it occurs and is usually developed as a granite-porphyry in which the phenocrysts are large quartzes. However, as one traverses the region from West Gull Lake through Red Rock to Saganaga Lake—that is, as one goes approximately from the periphery toward the center of the area—it is very noticeable that the grain of the rock, which is relatively fine upon the exposures on West Gull Lake, grows coarser toward the center. This is one of the evidences in favor of the intrusive character of the granite. In color the granite varies from light gray to pink, and even to brick red. This last strong tint is usually present where the alteration is the most pronounced.

The granite massive is cut in various places by fine-grained red aplite dikes.

Here and there in the granite may be found masses of dark gray to green rock. Some of them have been in planes along which movement has taken place, and are extremely altered, and have become schistose. Others have been much altered, but no actual motion appears to have occurred in them, so that they are still massive. These rocks are generally basic—some are even ultrabasic—and vary from basalts to peridotites. They are intrusive in the granite, but how much younger than the granite they may be is not known. The schistose basic rocks presumably belong to a period of eruption later than the Lower Huronian, and correspond to the dikes described in Chapter IV. The freshest basalts are presumably of Keweenawan age and are similar to those described in Chapter VI, under the heading "Keweenawan."

Microscopic characters.—Under the microscope the granite is found to be either a mica- (biotite-) granite or a hornblende-granite. This last is the predominant rock. It varies by loss of quartz to a syenite. Grant[a] has described still a different facies of the granite of Saganaga Lake—a fluorite-granite which he observed upon an island in Saganaga Lake. The essential minerals are mica, hornblende, quartz, orthoclase, and plagioclase. With these occur as accessory minerals, and in very small quantity, some apatite, sphene, and magnetite. These possess their usual characters and show the relations common to such minerals in the granites. All of the rocks are considerably altered. The usual secondary minerals—calcite, sericite, actinolite, epidote, and chlorite—have been produced and are present in the sections examined. The granite varies somewhat in textural character from the normal granite to a granite-porphyry.

In the granite-porphyries the phenocrysts are quartz, hornblende, and plagioclase. Around some of the feldspar phenocrysts there is occasionally micropegmatitic intergrowth of the feldspar with quartz. These minerals are distinctly of the first generation, and lie in a moderately fine-grained groundmass of hornblende, feldspar, and quartz of the second generation, in striking contrast in size to those of the first generation.

---

[a] Geol. and Nat. Hist. Survey of Minnesota, Twentieth Ann. Rept., 1893, p. 89; Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 323.

RELATIONS TO ADJACENT FORMATIONS.

The granite of Saganaga Lake is found in contact with and showing clearly its relations to the Archean Ely greenstone and the Lower Huronian sediments—the Ogishke conglomerate, and the Knife Lake slates.

Relations to Ely greenstone.—In the southern portion of the area underlain by the granite of Saganaga Lake, on the south shores of West Gull and Gull lakes, and along the contact between the granite and the Ely greenstone to the east of these localities, the granite penetrates the Archean greenstones in numerous dikes. Moreover, the intrusive nature of the granite is further shown by the fact that in the contact zone the greenstone is metamorphosed by the granite to an amphibolitic schist, whereas at some distance away from the contact zone—that is, beyond the influence of the granite—the greenstones show their normal characters.

On the northern side of the granite area, on the north and east shores of Cache Bay of Saganaga Lake (this is within Canadian territory), the same relations are clearly shown on a great number of exposures around the shores of the bay. Here, too, the metamorphism of the greenstones diminishes as the distance from the main mass of granite increases. Furthermore, the granite contains inclusions of rock derived from this greenstone.

On Red Rock, West Gull, and Gull lakes there are in places in the granite irregular fragments of hornblendic rocks that are believed to have been derived from the ancient greenstones through which the granites were intruded. This intrusive relationship of the granite and greenstone has been recognized by all geologists who have studied this area, except H. V. Winchell,[a] who maintains that the granite is derived from the greenstones, or Keewatin green schists, as he calls them.

Relations to the Lower Huronian sediments.—No such general agreement has been reached among the geologists who have studied the Vermilion district and the adjacent district in Ontario as to the relationship which exists between the granite of Saganaga Lake and the adjacent sedimentaries. A. H. Winchell[b] has decided that the granite is younger, as a granite, than the sedimentaries, and that it was derived from them by processes of progressive metamorphism. Lawson[c] describes it as intrusive in the sedi-

[a] Geological age of the Saganaga syenite, by H. V. Winchell: Am. Jour. Sci., 3d Series, Vol. XLI, 1891, p. 389.

[b] Winchell, A., Geol. and Nat. Hist. Survey of Minnesota, Sixteenth Ann. Rept., 1888, p. 211.

[c] Lake Superior stratigraphy, by A. C. Lawson: Am. Geologist, Vol. VII, 1891, p. 324.

mentaries, and having no other connection with them. Grant,[a] having first considered the granite as intrusive in the sedimentaries, examined it a second time, and since then has maintained that the sedimentaries are younger than the granite, having been derived from it.

The sedimentaries lie on the western flank of the granite area extending from Cache Bay of Saganaga Lake on the north to West Gull Lake on the south. Over a considerable portion of this area—for instance, where the drainage is imperfect—exposures are very few, thick morainal deposits covering that part of the area extending approximately from sec. 30, T. 66 N., R. 5 W., southward into sec. 5, T. 65 N., R. 5 W. At the extreme north and the extreme south, however, Saganaga and West Gull lakes, respectively, lie along the contact and give fairly good opportunities for a study of the existing relations. On the northern exposures especially the relations are so absolutely clear and convincing that the phenomena there observed will be first described.

Following the international boundary route from west to east, one passes in order through the long, narrow lakes of Knife and Otter Track (Cypress), then through Oak (Swamp) Lake into a bay of Saganaga Lake. The rocks exposed on these lakes are chiefly slates and graywackes, with occasionally a fine interstratified conglomerate. On Knife Lake the strike of the slates is about N. 70° to 80° E. As we go eastward we note a change in this strike, and when the east end of Otter Track Lake is reached the strike has become N. 45° E. to N. 20° E. and N. 10° E., and even in places is shown as nearly north and south. From Otter Track Lake we cross on the portage a ridge of the slates and then enter Oak Lake (Swamp Lake), where there are exposed over the greater portion of the shores the same dark slates and graywackes that are found on the lakes farther west. On this lake the strike of these sediments has turned until it is west of north. On the east side of the lake the sediments are noticeably different in character from those we have been observing. They are no longer dark, but are light in color—pink to reddish—and instead of being fine slates are predominantly coarse-grained arkoses. They show distinct bedding and dip, and one can trace gradations from the coarsest-grained rocks into the finer-grained ones. This alternation was noted by earlier observers, but was misinterpreted. These coarse arkoses so closely resemble

[a] Grant, U. S., Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 322.

the granite of Saganaga Lake (they are derived directly from it) that they were actually taken for that granite, altered, however, and were supposed to have been intruded in thin sheets parallel to the fine-grained beds lying in alternation with them. This was Grant's idea upon his first visit, when he decided that the granite of Saganaga Lake was for this reason younger than the adjacent sediments.[a] A subsequent visit caused him to change his view to the correct one, upon recognition of their true relations. The sedimentary characters of these bedded arkoses were noted by N. H. Winchell,[b] and likewise the resemblance of these arkoses to the granite of Saganaga Lake, the main mass of which lies east of and beneath these sediments, and the relations were interpreted by him as evidence of progressive downward metamorphism, the arkoses having been fused and transformed into the granite of Saganaga Lake. Examined under the microscope, these bedded rocks are seen to be made up of fragments of quartz and feldspar and flakes of mica. None of the minerals are well rounded, but neither do they show the same relationships to each other that the same minerals always exhibit in unquestionable granites. Moreover, the well-marked sedimentary banding in them and the gradation from coarser- to finer-grained rocks show that these are without question fragmental rocks or arkoses derived from the granite and consisting of the same constituents as the granite from which they were derived. These fragments of minerals have not been very much worn, and, since they were deposited here through the action of water, have been cemented together so as to form a rock that is strikingly like a granite, especially to one making a superficial macroscopic examination. A microscopic study, and indeed a close macroscopic field study, immediately discloses the characters above mentioned, and shows that they are different from the granite. Excellent exposures of the arkose occur on the portage from Oak Lake to the west bay of Saganaga Lake, and good exposures of the fragmentals showing distinct bedding may be seen on the north shore of this bay, on the point just east of the portage. After passing along these outcrops of sediments one finally comes to the clearly recognizable typical massive granite-porphyry of Saganaga Lake. These rocks have the distribution shown upon Sheet XVI in the accompanying atlas.

[a] Geol. and Nat. Hist. Survey of Minnesota, Twentieth Ann. Rept., 1893, pp. 90–95. [b] Loc. cit.

Farther east and north on the shores of Cache Bay of Saganaga Lake the relations between the granite and these sediments are shown still more conclusively, if that be possible, than at the localities above referred to. On the southwest side of Cache Bay, at a number of excellent exposures, the granite of Saganaga Lake is overlain to the west by a beautiful typical coarse basal conglomerate. This conglomerate is made up almost solely of bowlders of all sizes, derived directly from the immediately adjacent granite of Saganaga Lake. The matrix between these larger fragments is the finer detrital material derived from the same source.

The unconformable relations of the sediments known as the Ogishke conglomerate and the Knife Lake slates, here classed as Lower Huronian, to the granite of Saganaga Lake and the Ely greenstones of this eastern portion of the district are clearly shown by the above-stated field occurrences.

On West Gull Lake exposures are not nearly so good nor so extensive as on Saganaga Lake. Nevertheless, from a study of this area correct conclusions concerning the relations of the rocks were reached, and the later study of the Saganaga Lake area merely served to emphasize their accuracy. The areal distribution of the rocks within a small part of the district on the west shore of West Gull Lake is shown on the accompanying map, fig. 17. Starting in at the granite outcrop between the two meander corners at a point about one-fourth of a mile north of the southeast corner of sec. 7, T. 65 N., R. 5 W., we find that the granite along the shore shows its normal characters and is cut by several dikes of basic rock. As we follow the exposure inland, however, the granite is found to become more and more schistose, and finally we notice that this schistose rotten rock is made up of small granitic fragments, with the finer granitic débris for cement. Its fragmental character is most clearly shown by an occasional very small fragment of jasper. In examining this exposure one can say, when the extremes are seen, "Here is a granite, and here is a clastic derived from the granite;" but no sharp line of demarcation between them can be drawn, for, indeed, there is no such sharp line. On the contrary, there is an imperceptible gradation from the one to the other through the intermediate schistose material which probably represents the disintegrated portion of the granite which was not removed by erosion. In several other places, where the granite and sedimentaries come nearly together, they are separated by a narrow area usually marked by a small topographic depression in which no rocks are exposed or in which there is only an occasional isolated exposure of rotten schistose rock. In such exposures the characters

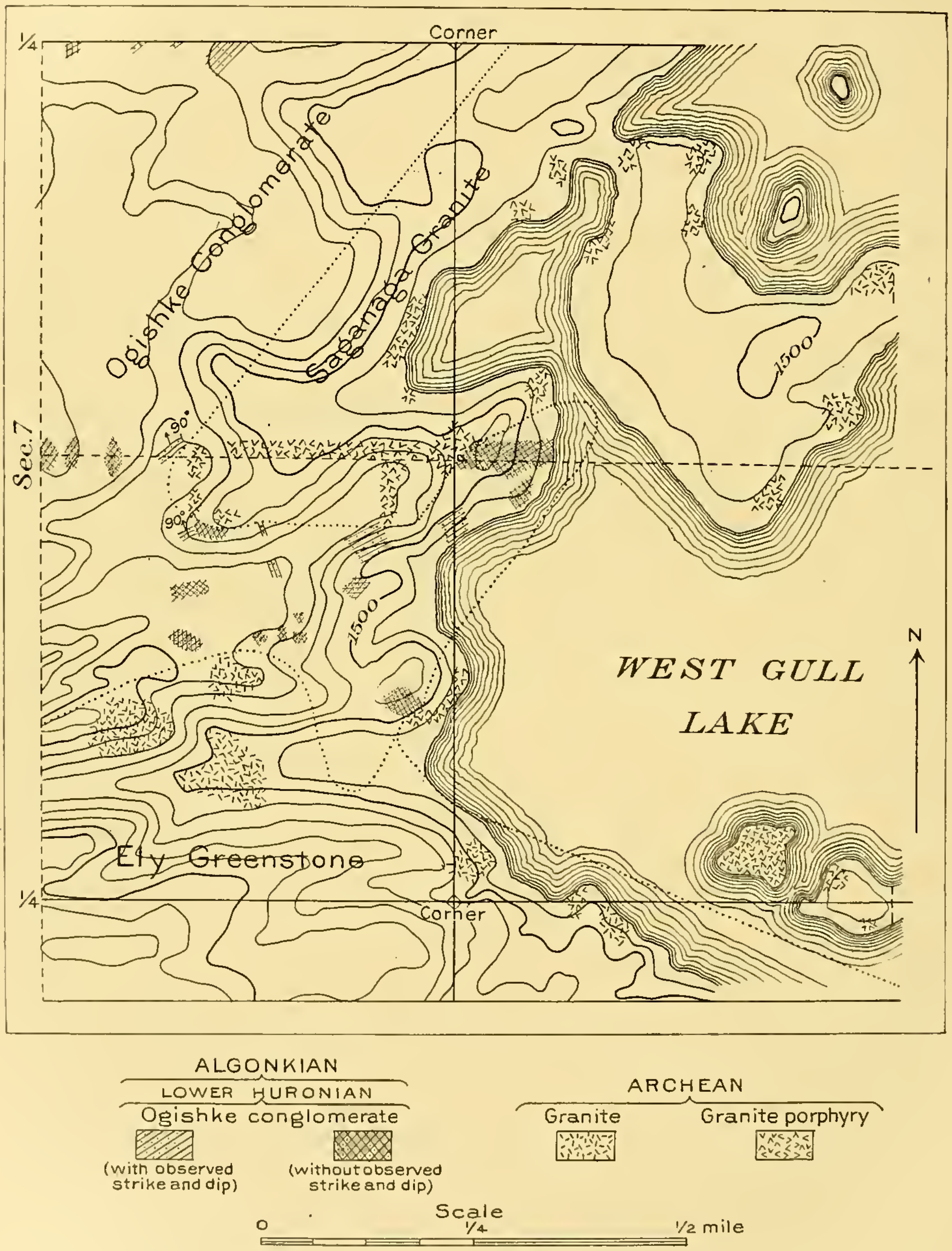


FIG. 17.—Detail geologic map showing exposures in a small area on West Gull Lake.

of this rock can not be definitely recognized in all cases, but since it is analogous in all respects to the material described above as occurring between the granite and the clearly recognizable sediments, it is assumed to be the schistose arkose that lies between the granite and the overlying sediments. These sediments consist of interbedded slates, graywackes, and conglomerates, and in these conglomerates pebbles were observed which could be identified with the granite of Saganaga Lake. After a study of the exposures here there can be no reasonable doubt that the sediments are younger than, and partially derived from, the adjacent granite of Saganaga Lake.

Within the area shown on the map forming fig. 17 there is a knob of greenstone, penetrated by numerous dikes of granite, similar to those occurring in the greenstone adjacent to the granite of Saganaga Lake at other places in this district. These dikes are presumed to be offshoots from the granite. Overlying this granite are sediments similar to those overlying the not far distant granites, consisting to a considerable extent of pebbles of granite and greenstone, showing them to be younger than both the greenstones and the granite. Within this small area, therefore, we find the Archean greenstone, the granite of Saganaga Lake, and the Lower Huronian sediments, with their relations to one another clearly shown. The Lower Huronian sediments are now folded into synclines within the granite and greenstone, and hence wrap around these rocks, as is shown on the accompanying map (fig. 17).

METAMORPHIC EFFECTS OF THE GRANITE OF SAGANAGA LAKE.

The granite of Saganaga Lake having been found intrusive only in the greenstones of Archean age, we are able to study its metamorphic effects upon these rocks alone. These effects are in all respects the same as those produced upon the similar greenstones by the intrusion of the granites of Trout, Basswood, and Burntside lakes, as the result of which amphibolitic schists were produced. The processes of metamorphism induced by these intrusions and the products resulting therefrom have been described in preceding portions of this monograph (p. 156 et seq.).

INTERESTING LOCALITIES.

Exposures of the granite of Saganaga Lake are so extensive in the area in which it occurs that it is unnecessary to refer to any special locality at which its characters may be studied. There are, however, several places at which the relations between the granite and the adjacent rocks may be noted with advantage, and although these have already been mentioned, attention will be again called to them.

The relations of the granite of Saganaga Lake to the Ely ellipsoidal greenstone may be seen at almost any place along the contact between the two on the south shore of Gull Lake. For instance, just below the north section lines of secs. 22 and 23, T. 65 N., R. 5 W., numerous dikes of the granite cut the greenstone. The greenstone near the contact with the granite, where it is full of granite dikes, has been extremely metamorphosed. The farther we go southward from the contact the less altered is the greenstone and the better preserved are the ellipsoidal, amygdaloidal, and other structures. The southwest shore of West Gull Lake and the small lake on the portage route between West Gull and Gull lakes are easily accessible, and here in the cliffs many dikes of granite cut the greenstone. The same relation is very clearly shown on the northeast shore of Cache Bay, which is the large bay of Saganaga Lake that extends into Canada. Along this shore innumerable dikes of the granite cut these schists.

The granite of Saganaga Lake is found in contact also with the Ogishke conglomerate, and its relation to the Ogishke conglomerate is well shown at certain places (mentioned above, pp. 269–273) on the west side of West Gull Lake, on Saganaga Lake, and on Cache Bay of Saganaga Lake. At all of these places the conglomerate consists largely of bowlders and finer detrital material derived from the granite. The rocks along the contact have in places been closely folded, and as a result of this folding the contact between the two is somewhat irregular and the relations appeared to be complicated, but careful studies of the exposures have shown the relations above stated.

CHAPTER IV.

THE LOWER HURONIAN.

SECTION I.—SEDIMENTARY ROCKS.

OCCURRENCE AND SUBDIVISIONS.

The Lower Huronian sediments of the Vermilion district have a very large surface extent. They are present in two large detached areas—one, known as the Vermilion Lake area, extending eastward from the western limit of the area mapped near Tower, on Vermilion Lake, to within about 11 miles of Ely; the other, known as the Knife Lake area, beginning about 7 miles west of Ely and extending eastward to the eastern limit of the area mapped. These same rocks extend farther eastward for an unknown but great distance, passing north of and around the granite of Saganaga Lake into Canada. Where the Vermilion and Knife Lake areas approach each other—that is, west of Ely—the rocks have their least surficial extent, rapidly widening as we follow them from this point eastward or westward. This distribution is due to the fact that the sediments occur in two great synclinoria. The short distance of about 5 miles by which the continuity of the rocks is interrupted represents the place where, as a result of a cross anticline, the lower (Archean) rocks have been brought to the surface. This gap is so narrow, and the structure points so clearly to the original extension of the sediments across it, that this lack of continuity is not considered important. Clearly the rocks of the two areas were continuous before erosion separated them. Considered in a broad way, the sediments of the Lower Huronian are fragmental rocks consisting predominantly of conglomerates and slates, although fragmentals intermediate between conglomerates and slates are, of course, present.

It is difficult to estimate the relative quantity of the several kinds of clastics included in the sediments. Moreover, they differ in respective quantity in different parts of the area. The conglomerates form by far the more striking portion, and the casual visitor to the district will notice beautiful exposures studded with brilliant-red jasper pebbles, and draw, perhaps, the conclusion that the conglomerate is the predominant clastic, but it is believed the slates make up the greater part of the sediments.

Included within the Lower Huronian there is a horizon of iron-bearing carbonates. These carry a considerable quantity of iron as carbonate in addition to the calcium-magnesium carbonates. There is also developed at a few localities an iron-bearing formation consisting of banded jasper, cherts, and iron ore. This iron formation is present in very small quantity, and certainly will never be of any importance on the United States side of the international boundary. These two kinds of rock are presumed to correspond to each other—that is, they belong to the same horizon. On the scale on which the map is published, it would be impossible to represent all of the different bands of conglomerates, grits, slates, etc. Consequently no attempt has been made to discriminate between these kinds of the fragmental rocks further than to show the areal distribution of the extremes.

We are enabled to divide the Lower Huronian sediments into three parts—(1) a lower division, which is predominantly conglomeratic and which is most typically developed near Ogishke Muncie Lake, and is called the Ogishke conglomerate; (2) a division represented only in the eastern portion of the district, consisting of iron-bearing rocks and known as the Agawa formation; and (3) a division which is predominantly a slate formation and which we shall denominate the Knife Lake slates, since these slates are well developed and splendidly exposed on and near Knife Lake. Mention has already been made of the fact that the Lower Huronian sediments occur in two separate areas within this district. In each area both the conglomerate and slate are well developed. There are, however, certain local differences in the rocks that underlie the Lower Huronian, and as a consequence the sediments in the two areas are slightly different. For this reason, and also as it simplifies exposition, it is considered best to describe the rocks of the two areas separately. It must in each case be clearly understood that the conglomerates of the two areas are geologically contemporaneous and that the same contemporaneity exists in the case of the slate formation. The Agawa formation is present, however, only in the Knife Lake area and can not be correlated with any definite formation in the western area. The areas will be described separately in the following pages.

VERMILION LAKE AREA OF THE LOWER HURONIAN SEDIMENTS.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Distribution.—The Lower Huronian of this area has been found to extend very much farther west than it is shown to do on the accompanying map (Pl. II). It has been carefully studied, however, only in the area outlined thereon, and in this description we must consider it as beginning at the western limit of the map, where the rocks of the series cover a very broad area, corresponding in width practically with the width of the map. Its greatest breadth is something like 11 miles in Ts. 61, 62, and 63 N., R. 16 W. As this area, as outlined upon the map, is followed to the east, we note that it is subdivided into a number of smaller areas by the various fingers of Archean rocks that project westward into it. Beginning at the south, the area underlain by Lower Huronian rocks is found to extend eastward very nearly to Bear Head Lake, and on the north from the Archean near West Two Rivers southward to the limit of the area mapped. Indeed, a reconnaissance shows conclusively that the same sediments continue beyond the limits of the map, and are practically bordered on the south by the Giants Range granite. The next area north of this projects eastward only so far as the town of Tower. It is but a short tongue, and is bounded on the south by the Archean greenstone and on the north by this greenstone and the associated iron-bearing formation which constitutes Lee and Tower hills. North of this there is a third tongue, occupying the valley between the anticlines of Tower and Soudan hills, projecting eastward at least as far as the village of Soudan. North of Soudan Hill, and occupying in general the basin in which Vermilion Lake lies, there occurs the main portion of the area underlain by the Lower Huronian sediments. This is also that part of the area in which the best exposures occur. The rocks of this area have been followed eastward as far as secs. 2 and 15, T. 62 N., R. 14 W. The main area of the Lower Huronian sediments around Vermilion Lake may be subdivided into a number of smaller areas, due to the structural relations of the rocks. On the east shore of Vermilion Lake, for example, there are a number of smaller tongues into which the area can be divided. These will not here be described in detail, but may be found outlined on the maps in the accompanying atlas. The length of this Lower Huronian belt from the western limit of the area mapped to the eastern end of the belt in which the exposures occur is about 17 miles. The Lower Huronian sediments within this area are subdivisible into conglomerates and slates, the formations occurring intermediate between these having been classed with one or the other, according to the predominance of the one or other kind of rock in the outcrops. The conglomerate of this area has been called the Stuntz conglomerate.[a] However, the two subdivisions of the series in the Vermilion Lake area are correlative with the Ogishke conglomerate and Knife Lake slates of the typical areas in the eastern part of the Vermilion district, and will be called by the same name in the description of the western area.

Exposures.—On the islands and on the shores of Vermilion Lake the exposures of the conglomerate are, on the whole, excellent, and are both frequent and of large size. In the inland areas, however, the exposures are not so numerous and are usually small.

The slates are not so well exposed on the islands and shore of Vermilion Lake as are the conglomerates, but exposures do occur, and they are usually of considerable areal extent, well cleared off, and good. There are likewise good exposures in the broad area underlain by the slates to the south and southwest of Tower, which is fairly well dissected by stream erosion. This statement is especially true of areas in the immediate vicinity of Pike River and along part of the course of West Two Rivers.

Topography.—Considered broadly, the Lower Huronian rocks of this area occupy relatively low ground, the higher elevations being formed by the Archean greenstones and the iron-bearing formation, this arrangement separating the Lower Huronian sediments into the various troughs which have already been described. The topography of the areas occupied by the Lower Huronian sediments has already been referred to (p. 36). It is fairly rugged, but there are no great elevations. The rocks have been carved into a series of north-northeast to south-southwest trending, rounded ridges separated by valleys occupied by swamps, streams, or lakes.

STRUCTURE.

Considering the western part of the Vermilion district broadly, it will be seen that the Lower Huronian sediments occupy a great synclinorium, trending N. 80° E., with Vermilion Lake lying in its broadest part, and that the sediments swing around the anticline of greenstone south of

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, pp. 282, 525–538.

Tower and spread out southward into a broad area in which exposures are so rare that no structural details can be determined. It is presumed, however, that this is also a great synclinorium, the south limb of which is bounded by the Giants Range granite, here beyond the limits of the map.

Within the Vermilion Lake area and immediately adjacent to it exposures are sufficient to enable us to determine some of the details of the structural features of the sediments in them.

In this part of the Vermilion district it will be noted that the conglomerate lies upon the flanks of the anticlinal hills formed by the older underlying rocks. Within the area covered by the Lower Huronian sediments alone, the Ogishke conglomerate occupies the anticlines, for example, at the Pike Bay oval, which is an anticlinal area. Ely Island is made up chiefly of the Ogishke conglomerate, but enough of the adjacent rocks are exposed to show plainly the structure. The conglomerate occupies the main central portion of the island—in fact, nearly all of the western two-thirds of the island—with but a small area of the Knife Lake slates flanking it on the south. In the eastern part of the island the conglomerate is intermixed with eruptive rocks, the granites of Vermilion Lake, from which it is derived and with which it is intricately infolded. On the eastern as well as on the western end of the island the conglomerates are coarser near the center, and grow finer and finer toward the sides. This change is most noticeable on the south side of the island, where at several places along the shore the Knife Lake slates grade into the conglomerate through graywackes of intermediate grain.

In general the slates occur in synclines lying between anticlines of older and harder rocks, and ordinarily these synclines coincide with the topographic depressions. In some places, however—as, for instance, north of Tower, between the west end of Soudan Hill and the point between Swede and Middle bays—the slates occupy a minor synclinorium and are extremely plicated. The slates of this particular synclinorium occupy at this place higher ground than the adjacent conglomerate on its flanks, and within this synclinorium the anticlines of slates are the structural features that occur at the greatest elevation. Structural details, such as strike and dip, were observed almost exclusively on the slates, and it is consequently by a study of the slate exposures chiefly, assisted by observations of the distribution of the other formations, that the structure of the series has been determined. It may be noted here that in the absence of any striking key rocks the folds in the slates were determined chiefly by the distribution of the slates and their variation in strike and dip.

The general strike of the slate beds is N. 80° E. The slates have been very closely compressed, and consequently many of the exposures show the most intricate plications. On the large folds, as well as on the plications, the strikes extend varyingly to nearly every point of the compass, the direction depending on the position on the fold of the place where the strike is taken. The dips are high and range from about 70° S. to 70° N. The northern dip is the more common and is generally not far from 80°. The axes of the folds trend approximately N. 80° E., and, as shown by the predominant northward dip of the beds, the axial plane of these folds is generally overturned, dipping slightly north. In addition to a south-north compression—to be exact, the pressure came from a direction slightly west of north and east of south—producing the folds trending east and west, there has been pressure at right angles to this, which caused a corresponding development of north-south folds. As a result of this minor cross folding, the axes of the major folds—the folds trending east and west—have a pitch varying from 90° to 65°. As a result of the compression, several sets of joints have been formed in the rocks. One trends from N. 60° to 80° E., in close agreement with the strike of the bedding and with the trend of the axes of the folds. Another set is nearly at right angles to the above, and varies from north and south to N. 10° W. The joints, however, evidently bear definite relations to the folds, having been produced by the same forces that caused the folding, for as the strike of the beds varies upon the folds the joints vary also. Thus on the point southeast of Sucker Point, where the beds strike N. 50° W., the joints strike N. 80° W. and N. 30° E. The close compression of these slates has produced a fissility which is very uniform throughout the region. It is very noticeable in the slates, and its general strike is N. 80° E., although a variation of a few degrees to south or north can be found. In general, there is an agreement of the strike of fissility and bedding, but, as Van Hise has demonstrated,[a] the fissility bears different relations to the

[a] Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Pt. 1, 1896, pp. 656–659.

beds in different parts of the folds. Thus on the limbs of the folds it is essentially parallel with the bedding, whereas at the ends of the folds it cuts across the bedding nearly at a right angle to it. No places were seen which appeared to promise a supply of good roofing slate. The rocks are very generally much broken up by minor joints, but at considerable depth possibly rocks might be found in such condition that roofing squares could be obtained.

These slates are everywhere intersected by numerous quartz veins, especially south of Pike River Bay. The presence of these quartz veins in the slates gave rise to the rumor of the occurrence of gold, and the early history of the Vermilion district is the history of attempts to obtain gold from veins in these sediments—as, for instance, at Gold Island, near the northern part of the lake.

RELATIONS OF OGISHKE CONGLOMERATE AND KNIFE LAKE SLATE.

The relations of the rocks to one another are so clearly shown at so many places that it is scarcely worth while to discuss them. There is a great conglomerate normally overlain by and grading up into a great thickness of slate through the intermediate graywackes. In the conglomerates occur masses of slate, and in the slate likewise occur masses of conglomerate. Evidently the series is a geologic unit which is divisible into two parts, the conglomerates and slates, only by an arbitrary line below which the conglomerate predominates on the whole, and above which the slates predominate. In an article on the Vermilion area Smyth and Finlay[a] described the slates as the oldest rocks of the area, instead of nearly the youngest.

RELATIONS TO ADJACENT FORMATIONS.

Relations to Archean.—Where the series is in contact with the Ely greenstone and the Soudan formation, the conglomerate normally lies next to these rocks, and consists to a great extent of pebbles derived from them. Hence, having been derived from them, it must overlie them stratigraphically and is therefore younger than they.

Occasionally the conglomerate occurs in very thin belts, too narrow to

---

[a] The geological structure of the western part of the Vermilion range, Minnesota, by H. L. Smyth and J Ralph Finlay: Trans. Am. Inst. Min. Eng., Vol. XXV, 1895, p. 602.

be shown on the map without great exaggeration. Sometimes the conglomerate is practically wanting, and then the slates abut against the Archean, although, as a rule, actual contacts of the slates and adjacent

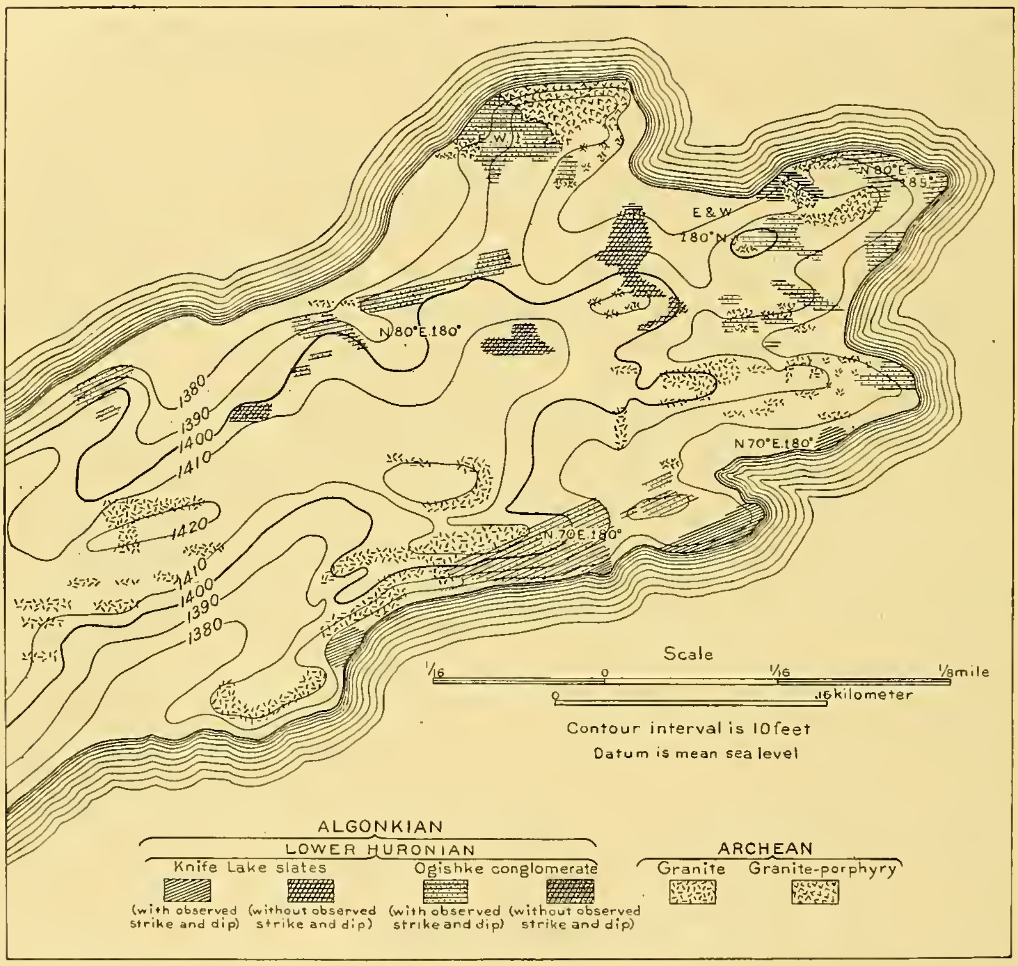


Fig. 18.—Detail map of the east end of Ely Island, Vermilion Lake, Minnesota, showing actual rock exposures, by J. Morgan Clements and C. K. Leith, 1899.

formations are wanting, erosion along the contact having removed the slates, which are softer than the other rocks at these places.

The relation of the sediments to the granites of Vermilion Lake is exactly the same as their relation to the greenstone and the iron formation. The basal conglomerate lies next to these eruptives normally and consists chiefly of pebbles, which can be identified with the rocks immediately adjacent. Moreover, in places, as we get farther from the eruptives, the gradation from the conglomerate to finer-grained sediments can be distinctly traced, showing plainly that the conglomerates were derived from the eruptives, and that consequently they are of later age. The conglomerates and eruptives especially have been very closely infolded and they now show the most intricate surface relations. The large-scale detailed maps of the east end of Ely Island (fig. 18), and of the point south of Mud Creek Bay (Sheet XXV of Atlas), will give some idea of the intricacy of their surface relations and will indicate the difficulties of successfully determining the geologic structure. This intricacy of relationship between the sediments and eruptives is in some places most puzzling. A sketch, fig. 19 (p. 290), made in the field, illustrates the relations between these two rocks which were seen on an exposure on the north side of Ely Island, near the east end, and which will be described in some detail further on.

The character of the conglomerate is usually well marked, especially when jasper pebbles are abundant in it. Under such circumstances the pebbles of the acid igneous rocks in the conglomerate can also be identified with the adjacent masses of granite and porphyry. But where both the igneous rocks and the conglomerate derived from them have been very much mashed, and especially where there is a comparatively fine-grained sediment—in other words, a grit—it is very difficult to discriminate between them, for both the igneous rocks and the grits derived from them have been sheared into white to gray fissile sericitic schists which have practically the same appearance. It is not improbable that some mistakes have been made on the detailed maps in this discrimination, but extreme care has been exercised, so that the mistakes are unquestionably few, and while they may affect the determination of the areal distribution of these rocks they are not of such character as to affect the interpretation of their general relations.

Relations to the Giants Range granite.—South of Tower, in the vicinity of milepost 92, on the Duluth and Iron Range Railroad, the Knife Lake slates are intruded and metamorphosed by a number of granite dikes which have been correlated with the Giants Range granite. The fact that this granite is younger than the Lower Huronian sediments is thus clearly shown.

Relations to basic dikes.—The Lower Huronian sediments, both the Ogishke conglomerate and the Knife Lake slates, are cut by occasional dikes of basic rocks, which are thus younger than the sediments. Splendid examples of such dikes can be seen on Stuntz Island and elswhere. Some of these dikes are older than, and some of them are essentially contemporaneous with, the Keweenawan rocks.

AGE.

The above facts concerning the relations of the Ogishke conglomerate and the Knife Lake slate to the adjacent formations are so conclusive that no doubt can remain as to the relative age of these sediments. They lie immediately on the Archean Ely greenstone and the Soudan formation, and are younger than these and than the granites of Vermilion Lake which penetrate these two latter formations. They are older than the Giants Range granite and than certain basic dikes that cut them. Since the sediments lie immediately upon the Archean and are overlain by another series of clastic rocks, as has been found from the study of the contemporaneous rocks in the Knife Lake area, they are here placed at the base of the Algonkian, and are correlated with the Lower Huronian series of the other iron-bearing districts of Lake Superior.

OGISHKE CONGLOMERATE.

This conglomerate was first so called because it is well developed on and near Ogishke Muncie Lake, and the use of the term has been continued on account of its appropriateness and because it was used in the early literature of the Vermilion district.

Attention is again called to the statement already made, that the conglomerate in some places differs somewhat petrographically from that of the typical area, and that this variant phase has occasionally been called by the local name of Stuntz conglomerate. (See p. 278.)

PETROGRAPHIC CHARACTERS.

Macroscopic characters.—The conglomerates in this western area all possess a strong family resemblance. On the weathered surface the different beds are white or grayish in color. This light color is due to pebbles of rhyolite-porphyry, microgranite, granite, and granite-porphyry, which, as a rule, have very light-colored weathered surfaces and are the main constituents of the conglomerates. In a few places there is a good deal of jasper present in angular fragments of various sizes. Greenstone fragments are found occasionally, but they are much rarer than one would expect them to be. In addition to the kinds of rock already enumerated, pebbles of black and gray chert and yellowish-green sericite-schists were observed.

The conglomerates differ locally in degree of coarseness, varying from coarse-grained conglomerates, with bowlders reaching 2 feet in diameter, to those in which the majority of pebbles are about 4 to 5 inches in diameter. This latter facies is the commoner. Associated with these conglomerates there are of course considerable quantities of much finer-grained rocks, which would naturally be called consolidated grits or graywackes, but which are here mapped with the conglomerates. With these are likewise occasionally areas of slate. On the map an attempt has been made to discriminate, by means of the colors, between the conglomerate and the slate, but a close examination in the field would reveal the fact that in some of the areas marked as conglomerate there are in places considerable quantities of graywackes and slates associated with and lying in the midst of the conglomerate. The areas of these rocks are so small in proportion to the area of the conglomerates that no attempt has been made to show them on the small scale maps published herewith.

It is interesting to note the dependence of the petrographic character of the conglomerate upon the adjacent rocks from which it was derived. Where, for example, it lies next to a certain characteristic porphyry, the major portion of the conglomerate is formed of pebbles and fine detritus of the porphyry. On the other hand, where the conglomerate lies near the iron-bearing formation, fragments of this formation become numerous, although ordinarily they are scarce. The pebbles and bowlders in the conglomerate are crossed by fracture lines which divide the individual pebbles in it into more or less rhomboidal fragments. This fracturing of the fragments and the occurrence of the pieces essentially in place shows that the dynamic action that produced the fracturing took place after the formation of the conglomerate and that only slight displacements occurred as the result thereof.

ORIGIN OF THE CONGLOMERATES.

When we study these conglomerates in the field and find that they are made up of pebbles of various kinds of rock lying in a fine-grained clastic matrix, the pebbles of a certain kind of rock being most numerous near an underlying mass of the same kind, and when, moreover, we find beds of grits and slate alternating with the conglomerate, all of these showing every gradation into one another and possessing both true bedding and false bedding, the only satisfactory conclusion we can form concerning the origin of these rocks is that they are true clastic conglomerates of sedimentary origin. This mode of origin seems so obvious that its statement appears almost uncalled for, and it is made only for the reason that a strong argument has been made by previous students of the rocks of this area for the brecciated origin of these conglomerates.[a] Reference has already been made in previous pages to the formation of pseudo-conglomeratic rocks from the granites of Vermilion Lake by dynamic processes. The first description of these pseudo-conglomerates (friction conglomerates) and the correct explanation of their origin was given by Smyth and Finlay in the article above referred to. They made the error, however, of attributing this method of formation to all of the conglomeratic-looking rocks of that part of the lake and adjacent shores which they studied, including great masses of true normal conglomerates occurring in great abundance on Stuntz Island, Stuntz Bay, and elsewhere. These rocks, it is true, are intimately associated with the pseudo-conglomerates, but in most places may be readily separated from them. That the true conglomerates were unquestionably included with the pseudo-conglomerates is shown by the fact that reference was made to the conglomerates occurring on Stuntz Bay and Island as examples of pseudo-conglomerates,[b] whereas in reality they are typical sedimentary conglomerates in which may be observed the characters referred to above as proving indisputably their sedimentary origin.

THICKNESS.

The bedding in the coarse conglomerate is poor, but grows more distinct as the grain gets finer until, as in the rocks here called graywackes, it becomes very distinct. It is, however, generally so obscure that it has not been possible to determine it with great accuracy and frequency. Moreover, the rocks have been extensively folded, and considerable reduplication—which it has not been practicable to determine—may have taken

[a] Geological structure of the Vermilion range, by H. L. Smyth and J. Ralph Finlay: Trans. Am. Inst. Min. Eng., Vol. XXV, 1895, pp. 610, 629.

[b] Op. cit., p. 612.

place, and would vitiate any estimates. For these reasons it has been found impossible to determine, even approximately, the thickness of the conglomerate. In places it is wanting or is represented merely by a thin mass. In other places, as, for instance, on Vermilion Lake, it shows great development and must be very thick.

INTERESTING LOCALITIES.

The islands in Pike Bay offer good exposures of the typical Ogishke conglomerate of the western area. There are also splendid exposures on the large island in sec. 14, T. 62 N., R. 15 W., and on both sides of Armstrong Bay. Smaller exposures occur nearer Tower, one southwest of Tower in SW. $\frac{1}{4}$ of sec. 6, T. 61 N., R. 15 W., another just on the outskirts of Tower, on the south slope of Lee Hill, and another on the south slope of Soudan Hill.

One of the best places in which to study this conglomerate in its typical development is on the southwest side of Stuntz Island, which lies across the mouth of Stuntz Bay of Vermilion Lake. On the bare exposures here the conglomerate is made up of pebbles and bowlders of granite-porphyry, porphyritic micrograuite, rhyolite-porphyry, a feldspathic porphyry, jasper, and comparatively rare fragments of greenstone. The coarsest conglomerate lies near the center of the island and is separated from the acid intrusives to the north by a marked depression. Pebbles of the intrusives are present in the conglomerate. As we go southward across the exposnres the conglomerate grows finer and occasional beds of grit, striking east and west, occur in it until finally on the extreme southwestern point of the island there may be seen at low water a few feet of typical Knife Lake slates. The evidence here is conclusive that the conglomerate has been derived from the sediments to the north and that there is a gradation from it into the Knife Lake slates to the south. On the highest knob at the west end of the island the conglomerate is penetrated by a number of basic dikes varying from $1\frac{1}{2}$ inches to 6 feet in width. At one place near the highest point nine dikes were counted within a distance of 60 feet, lying essentially parallel and trending a little south of east. These dikes cut across the schistosity and the bedding of the conglomerate and also across the fragments in it, showing sharp contacts. They do not seem to have produced any contact effect on the conglomerate. The dikes themselves are only very slightly schistose, and the schistosity is confined to the edges.

On the hill just south of Mud Creek Bay the conglomerate is exposed at a number of places. As a result of the close folding it appears in very complex relationship with different rocks, namely, the Ely ellipsoidal greenstone and the various granitic rocks of Vermilion Lake. After a careful study of the exceedingly intricate contacts between the porphyries and the conglomerates, which at first led to the belief that the porphyries were intrusive in the conglomerates, it was found that this relationship was due to the close infolding of the rocks, giving zigzag and most irregular contacts. This relationship, as has already been stated in previous pages, was proved by the identification of the porphyry pebbles in the conglomerate with the adjacent porphyries. The detailed map, Sheet XXV of the atlas, shows the areal distribution of these rocks on this point and will give some idea of the intricacy of the distribution.

Reference has already been made to the rocks occurring on Ely Island. A good place at which to study the close relationship of these rocks is the east end. Here there is a most intricately folded complex of moderately fine-grained granite-porphyry, conglomerate, and graywacke. The distribution of these is shown on the detailed map forming fig. 18. The graywacke and porphyry when looked at casually resemble each other very strongly, but when examined closely they can readily be distinguished. The porphyry is studded with small phenocrysts of quartz and, as a result of weathering, develops an exceedingly rough surface in detail, something like a nutmeg grater. The graywacke contains grains of quartz which in many cases, and probably in most cases, are phenocrysts derived from the porphyry and in some instances are very slightly worn. This graywacke weathers in general with a smooth surface, and this difference in the weathering alone will usually enable one to distinguish the two kinds of rocks. Where the graywacke is in very massive exposures, and especially where the graywacke and porphyry have both been sheared, it is at times extremely difficult to separate them. As the result of the shearing and subsequent weathering both the porphyry and the graywacke are likely to develop a series of small parallel ridges or corrugations on the surface. This corrugated way of weathering was not so noticeable, however, on the porphyry as on the graywacke. At this place the infolding of the porphyry and the sediments is exceedingly complex. We find fingers of the one interlocked with fingers of the other, so that the contact forms a zigzag line, each finger pointing to a small fold—anticline or syncline. The plane of contact between the porphyry and the sediments varies greatly. In most cases the porphyry is below the sediments, but in some cases the fold is clearly overturned, so that now the conglomerate frequently lies under the porphyry. Between these extremes any position of this contact plane, from flat to vertical, may be seen. This irregularity in the position of the plane caused considerable confusion at first in the determination of the rélationship between the rocks. For some time it was thought that the porphyry was intrusive in the sediments. However, further study showed that the conglomerate was clearly derived from the porphyry and that the relationship mentioned was due to close folding. A further factor which led to confusion was that the porphyry itself simulated somewhat a conglomerate, for it is marked by two series of fracture lines lying close together and crossing each other at such an angle as to produce small rhomboidal blocks. Further shearing took place along these planes of parting, and eventually the angles of the fragments were more or less completely rounded, and the areas between the subangular fragments were filled with schistose material. On exposed surfaces the massive unfractured parts of such rocks weather less readily than do the schistose portions lying between them, and consequently stand out as small rounded projecting areas very similar to the pebbles in a conglomerate, which project above the surrounding matrix. Closer examination of such surfaces, however, shows that the fragments are all of one kind of rock and that the apparent matrix lying between them is but sheared material of essentially the same nature as the massive portion. This is the most obvious fact noticed in a study of them and enables one readily to separate such fractured and sheared porphyries from the true conglomerates derived from them, which are made up invariably of fragments of different kinds of porphyries, with more or less abundant jasper fragments and an occasional fragment of greenstone. The strike of the axes of the main folds at this locality is about N. 80° E., showing that the force that produced the folding was exerted along a line extending approximately north and south. As the result of this compression schistosity has been developed in the sediments and in the underlying intrusives. This schistosity cuts directly across the minor folds shown in the zigzag contacts above described and continues from the sediments into and through the igneous rocks. The schistosity, which strikes about N. 70° E., cuts at a sharp angle the sedimentary bedding, which varies from N. 80° E.

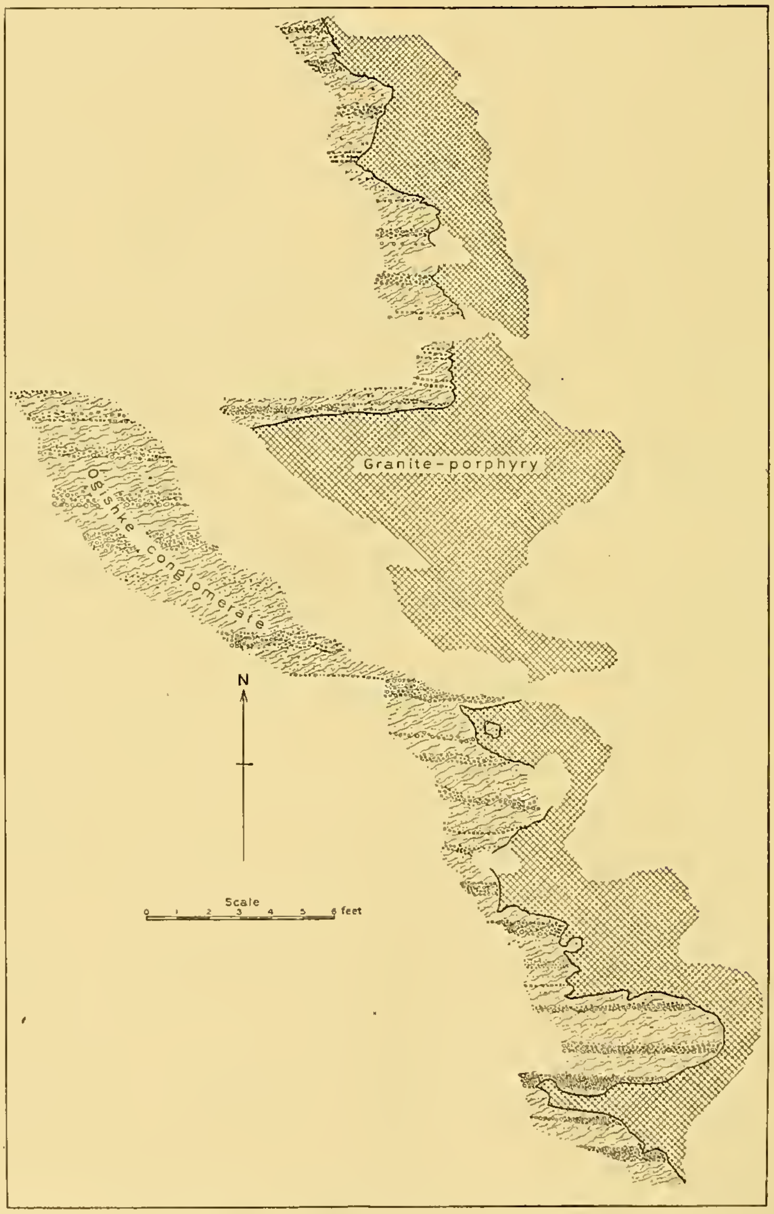


Fig. 19.—Sketch showing intricate relationship of granite-porphyry and overlying Ogishke conglomerate on Ely Island, Vermilion Lake.

to east and west. The dip of the bedding varies slightly from 75° to the north to vertical. Indeed, it is occasionally found with a dip of 85° and even 80° to the south, although the steep northward dip is the one which unquestionably predominates. The sketch reproduced in fig. 19, which was drawn to scale in the field, illustrates very well the intricacy of the contact between the sediments and the igneous rocks and shows other features which at first tended to create a belief that the porphyry was in igneous contact with the sediments. The exposure reproduced occurs on the hill at the west side of the first bay west of the northeast point of Ely Island and on the north shore of the island. Going along the contact between these rocks, one finds the contact plane lying at different angles, but on this particular exposure the folding has not been so great as to overturn the rocks and place the conglomerate under the igneous rock. Just north of the first main fold at the south end of the exposures sketched are a number of very small flutings, and one of these is represented as it occurs in nature—as connected with the main mass of sediments merely by a small neck. A little farther north of this place, on the hill, there was observed a small mass of conglomerate, represented in the sketch, which was completely separated from the sediment and surrounded by the igneous rock. This evidently was closely infolded in the igneous rock and afterwards separated by erosion from the main mass. Here the process of separation has been completed, whereas in the mass previously described erosion had gone only far enough to leave merely a narrow neck connecting it with the main area. This isolated area of conglomerate appeared much like an inclusion of conglomerate in the porphyry, and was so construed at first, but later more detailed studies showed its true character as an infolded mass.

On the east side of Stuntz Bay of Vermilion Lake the conglomerate is well developed and is exposed over large areas having white weathered surfaces. Here, as at the other places noted, the conglomeratic character is plain, the fragments being well rounded and ranging from minute pebbles to bowlders 2 feet or more in diameter. At one place there is a coarse conglomerate made up of fairly irregular bowlders, such a conglomerate as is often deposited near a shore line on which the wave action has not greatly rounded the fragments. Immediately in contact with this coarse conglomerate is a belt, about 4 feet thick, of beautiful, regular conglomerate, such as would be produced by the consolidation of a shingle beach. The majority of the pebbles of this bed vary from 1 to 6 inches in diameter. The conglomerates have not been very much metamorphosed.

The pebbles have been frequently crossed by fractures which divide them into rhomboidal pieces, but have not in general been greatly deformed. The fragments usually retain their relative positions. At least 90 per cent of the pebbles in the conglomerate are rhyolite- and feldspar-porphyry, granite-porphyry, and microgranite, the last of which occurs in numerous exposures in the immediate vicinity. Intermingled with these in very small quantity are fragments of jasper and greenstone. The fragments of porphyry are well-rounded pebbles, and the conglomerates grade into the finer-grained grits and slates and are occasionally traversed by bands of this finer-grained material, so that there can be no question whatever that they are normal water-deposited conglomerates.

South of Tower, near milepost 92 on the Duluth and Iron Range Railroad, there is a cut which passes through the Ogishke conglomerate and the associated Knife Lake slates. The conglomerate is very well exposed on the east side of the road, where the weathered surfaces give one a better opportunity to study the different kinds of pebbles in the rock than can be had in the small fresh exposures in the cut. The conglomerate is of essentially the same character here as at the exposures near Vermilion Lake. The Knife Lake slates lie north and south of it, and the conglomerate and the overlying slates have been intruded by both acid and basic dikes, the acid dikes apparently corresponding to the Giants Range granite, which forms the main portion of the Mesabi or Giants range bordering the northern portion of the Mesabi district. This occurrence of the conglomerate at this place is evidently due to a subordinate anticline which raised it, erosion having then removed the superimposed slates and exposed the conglomerate as we now find it. The sediments here have all been altered, and now the matrix of the conglomerate and the finer-grained bands that occur occasionally in it have been metamorphosed to amphibole and especially to mica-schists, whose origin could not be determined but for their association with and gradation into undoubted sediments.

In the SW. $\frac{1}{4}$ of sec. 6, T. 61 N., R. 15 W., at the second falls above the bridge on the county road, on the west bank of West Two Rivers, there is a cliff consisting of Ogishke conglomerate. This conglomerate is here only a short distance from ellipsoidal greenstone of the Ely formation, which is exposed on the east side of the river, and it consists of numerous pebbles of schistose greenstone, evidently derived from the underlying

Ely greenstone, as well as predominant pebbles of the granite rocks of Vermilion Lake. This is the point nearest to the basal greenstone at which the conglomerate has been found in this part of the district.

Another basal conglomerate somewhat similar to the one just described occurs on the south side of the county road leading from Tower to Pike River, about 325 paces east of the bridge over West Two Rivers. This conglomerate has been sheared until it is quite schistose. It consists chiefly of fragments of greenstone, jasper, and feldspar-porphyry.

KNIFE LAKE SLATES.

The conglomerate described in the preceding pages is overlain by the important Knife Lake formation, which is excellently developed upon the shores of Vermilion Lake in the vicinity of Tower. The name is given to the formation on account of its typical development near Knife Lake (p. 297).

PETROGRAPHIC CHARACTERS.

It has been stated that the dividing line drawn in the Lower Huronian sediments between the Ogishke conglomerate and the Knife Lake slates is purely arbitrary. The transition between them is not sharp. Among the conglomerates there are a few interbedded fine-grained sediments, and among the slates there are a few fragmentals that are coarser than the normal slates, and show gradations between the slates and the conglomerates. However, the slates are by far the predominant kind of rock in the areas marked on the accompanying maps with the slate color, the grits playing a very subordinate rôle.

Corresponding to differences in mineralogic character there is in the slates considerable variation in color and texture. The normal slates are on fresh fracture generally a slate gray to dark-greenish gray, and even light greenish. Sometimes they range through purplish and bluish-black rocks to a dense and almost black slate. They usually weather with a light-gray to brown crust. The grain of the slates is so fine that one can distinguish no individual mineral, unless it be quartz, except in the phase that approaches the grits. The banding in the slates is caused by slight variations in the quantity of the minerals of different color constituting the slates, and by a slight difference in size of grain. These bands within the slates vary in thickness from a fraction of an inch to several feet. The bands of slate themselves, where interlaminated with grits and near the conglomerates, also vary in thickness from a few inches up to 30 paces. These slate beds show a gradual increase in thickness as they occur at a greater distance from the conglomerates. The slates are in places—as in the embayment between Tower and Lee hills—very heavily impregnated with pyrite, which is scattered through them in cubes, usually altered more or less to limonite.

Microscopic examination of the Knife Lake slates and associated gray-wackes shows that the primary constituents are feldspar, quartz, and hornblende in fragments. With these occur secondary products—chlorite, epidote, calcite, sericite, sphene, and pyrite. In the coarse-grained rocks the various constituents can readily be distinguished. In the finer-grained ones only the coarser particles can be clearly recognized, and these lie in a very fine-grained dark matrix whose characters can not be positively determined, but which probably consists of fine dust particles derived from the other constituents, with which may occasionally be associated some carbonaceous material (although this was not recognized as such) and ferruginous matter, the last being the chief cause of the dark color.

These slates vary from the normal slates described, which preponderate, to rocks found in certain portions of this area, which, although showing all the macroscopic features of bedded clastics, nevertheless under the microscope are seen to have been recrystallized, and now may properly be called mica- and amphibole-schists and gneisses. These mica- and amphibole-schists and gneisses vary from light-gray to nearly black rocks. The schists have a light-brownish weathering crust. One can distinguish in all cases in them the mica flakes, the amphibole, and very frequently the feldspar and quartz. Differences in color and size of grain produce a banding in these metamorphosed rocks. Usually the banding stands out much more plainly on their weathered surfaces than upon the fresh fracture planes. This banding in the schists unquestionably corresponds to lines of original bedding, for it can in places be traced uninterruptedly from the slates into the banded mica-schists, in both of which rocks it shows the same strike. Moreover, at one place south of Tower, on exposures east of the Duluth and Iron Range Railroad, near milepost 92, one may see these schists in various stages of formation, and on these schistose rocks there are still present most perfect examples of false bedding in the normal unmetamorphosed slates.

These metamorphosed slates consist of green hornblende, actinolite, mica (biotite, muscovite, and sericite), feldspar, quartz, chlorite, rutile, epidote, sphene, apatite, calcite, garnet, and iron oxide. In some of these the garnet and muscovite appear as porphyritic constituents full of inclusions of the other minerals of the rock, thus showing that their origin is later than that of these constituents.

THICKNESS.

The folding of the slates has resulted in excessive crumpling and a slight overturning with an average dip of about 80° N. That this condition exists is shown by a number of minor anticlines and synclines which have been observed. It is very probable, therefore, that the thickness of the slates has been several times repeated in the area. Bearing the above facts in mind, one will readily appreciate the statement that an estimate based on the width of the slates and the width of the area would probably give a thickness many times too great. As such an estimate would only lead to erroneous conclusions, and as we have no better means of making a more accurate estimate, no attempt is made to give the thickness.

INTERESTING LOCALITIES.

The general characters of the Knife Lake slates occurring in the western part of the Vermilion area can be seen at many places on the islands in Vermilion Lake and on the shores of the lake. The slates are well exposed on the east end of Sucker Point and on the adjacent shores of the mainland, and here one has good opportunities to examine them at localities that are readily accessible. The high hills east and southeast of Swede Bay, in the SE. $\frac{1}{4}$ of sec. 20, T. 62 N., R. 15 W., afford a number of bare rounded surface exposures of these slates, and here, too, the results of the intricate folding to which they have been subjected can be studied. Similar slates may be observed at several places on the south shore of Ely Island, on Canoe Island, and on the island south of its eastern end, and also on the south shore of Pine Island, as well as at a great many places on the lake. These slates are also exposed on the south slope of Soudan Hill, just above the road, and on the road at the crest of the small hill in the town of Soudan. Being near the base of the formation, the slates here contain small amounts of conglomerate and graywacke.

More interesting than these common phases are the slates which occur in the southern portion of the area, and which have been subjected to metamorphic action to such an extent that they have been transformed into mica- and amphibole-schists. Excellent opportunities for the study of these metamorphosed sediments are afforded by exposures near Pike River. The best places for such study, however, are in the cuts along the Duluth and Iron Range Railroad between Embarrass and Tower, and especially in those between East Two Rivers and milepost 92. On these exposures the sedimentary character of the rocks is clearly shown by sedimentary banding, false bedding, the presence of large bluish fragmental quartz eyes which stud some of the beds, and in the vicinity of milepost 92 by the fact that exactly similar sediments are there interbedded with the Ogishke conglomerate, into which the slates grade. Some of the sediments have been so extremely metamorphosed, however, that but for their field relations it would be impossible to recognize them with absolute confidence as derived from sediments. It should be noted that the sediments at these exposures are cut by granite dikes, and that the change in the sediments from normal slates to mica- and amphibole-schists coincides with the appearance of the dikes. The metamorphism of the rocks increases southward along the railroad, in which direction the dikes become more numerous as one approaches the large granite areas on the Giants range, from which the dikes are presumed to be offshoots. Winchell,[a] who has noted the metamorphism of the graywacke and the slates to mica-schists south and west of Tower, attributes this metamorphism to the Giants Range granite, but classes these sediments in his Keewatin division. The sedimentary banding, which still shows very plainly, even at places where the rocks have been metamorphosed to mica-schists, is evidently indicative of a difference in original mineralogic, and hence chemical, composition. In spite of the metamorphism these original differences have continued to exist, and hence the sedimentary banding is retained.

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 254, and Pl. LXVII and LXXXVI.

KNIFE LAKE AREA OF THE LOWER HURONIAN SEDIMENTS.

SUBDIVISIONS.

The Lower Huronian sediments are much better developed and more extensively distributed in the eastern than in the western portion of the Vermilion district. Knife Lake, a prominent topographic feature of the eastern part of the district, lies in the sediments, and therefore this portion of the district in which the sediments occur will be called the Knife Lake area.

The Lower Huronian sediments of the Knife Lake area may be conveniently subdivided into (1) the basal Ogishke conglomerate, (2) the Agawa formation (iron bearing), lying conformably above the conglomerate, and (3) the Knife Lake slates, which overlie conformably the preceding formations. Thus it will be seen that in this eastern area there is a tripartite division, whereas in the Vermilion Lake or western area the Lower Huronian could be subdivided into only the Ogishke conglomerate, and the Knife Lake slates, time equivalents of the Ogishke conglomerate, Agawa formation, and the Knife Lake slates of this eastern area. The intermediate iron-bearing Agawa formation of the Knife Lake area has no known stratigraphic equivalent in the western part of the Vermilion district.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Distribution.—The eastern area of the Lower Huronian sediments begins a few miles west of Ely, in sec. 4, T. 62 N., R. 13 W., and extends east for a long distance beyond the international boundary, which is the eastern limit of the portion of the district included in the accompanying map (Pl. II). Where these sediments begin at the west the area underlain by them is very narrow, and this tongue continues narrow for several miles to the east, gradually, however, widening out. Finally, in the vicinity of Moose Lake, the continuation of this narrow belt is found to join the main Lower Huronian sedimentary area. The distribution of these rocks for this part of the area will be mentioned later. To the south of the east-west trending area above mentioned there lies a narrow belt of sediments which begins on Farm Lake, extending about east and west. This belt lies along both sides of the North Branch of the Kawishiwi River, extending southward below this for some distance, where it abuts against the intrusive granite and continues eastward into sec. 29, T. 63 N., R. 10 W. The continuation of these sediments to the east is also interrupted by the intrusive granite. The same series of sedimentary rocks is again found east of the above-mentioned granite in sec. 20, T. 63 N., R. 9 W. From here they have been traced to the northeast, where they are found to connect with and to form part of the same large area south of Moose Lake into which the northerly tongue previously mentioned merged. In this portion of the district, that is, in the vicinity of Moose Lake, the Lower Huronian sediments are found to extend over the greater portion of the area surveyed. These sediments are, however, subdivided into several partly disconnected areas or tongues by intervening areas underlain by Archean rocks as well as by intrusive masses of acid rocks somewhat younger than the sediments. Continuing our observations on the distribution of the Lower Huronian sediments from the area west of Snowbank Lake, we note first that on the south this area is disconnected from an area underlain by related rocks on the southeast side of Snowbank Lake by the intervening Snowbank granite. This belt, however, extends around the east side of the Snowbank Lake area and connects on the northeast with the similar sediments which sweep around the northwest side of the lake. Where these join, to the northeast and east of Snowbank Lake, they underlie an area which has very nearly the same width as the Vermilion district. This main mass of the sediments continues on east over Ensign and Knife lakes. To the south of Knife Lake the main area underlain by the sediments is interrupted by small areas of Archean rocks as well as by the Cacaquabic granite, which is younger than the sediments. To the east of Ogishke Muncie Lake the Lower Huronian sediments are divided into two main belts by a westward-projecting massive of Archean greenstone which lies immediately south of the granite of Saganaga Lake and in juxtaposition with it. These belts, a southern and a northern one, can be traced around the interrupting Archean greenstone and granite of Saganaga Lake for a great distance beyond the Canadian border to the north of this separating area. On the south this sedimentary series ends just east of Gobbemichigamma Lake, in sec. 30, T. 65 N., R. 4 W.

Exposures.—The country underlain by the conglomerates and slates is cut up by numerous lakes and is for the most part bare of timber of large growth, partly by reason of extensive forest fires and partly for lack of good and abundant soil; consequently the exposures of these sediments are numerous and usually of exceptionally large size.

Topography.—The topography of the Knife Lake area of the Lower Huronian sediments is very rough, although the features as a whole are on a comparatively small scale. In general the topography in this area is much more accentuated than it is in the area underlain by the same sediments in the western portion of the district already described (p. 278). The maximum difference in elevation is 400 feet, the difference between the level of Ogishke Muncie Lake and the adjacent hills. Reference has already been made (see p. 45) to the fact that the lakes in this part of the district are relatively deep, as has been shown by the few soundings taken. The maximum depth found in a lake in the sediments is nearly 200 feet. In reality, then, the difference between lowest valleys and lake basins and highest hills is about 600 feet. The hills and ridges have the usual east-northeast-west-southwest trend, with narrow, deep valleys occupied by streams and lakes lying between. The slates, on the other hand, generally form the lower hills. These, while occasionally rounded, are generally more or less angular, more nearly corresponding to the appearance of the slate hills in nonglaciated territory, although by no means so angular as these.

Normally the conglomerates occupy higher levels than do the slates which lie next to them, and these hills of conglomerate have fairly well-rounded contours. In portions of this area, however, the slates are very siliceous, and as a result of their great hardness form some of the highest hills. In the area underlain by slates sheer cliffs are common, some of them reaching a height of 100 feet above the lakes.

The topography has been greatly influenced by the structure. This will be referred to in the succeeding paragraphs.

STRUCTURE.

The Lower Huronian sediments, from the westernmost point where they are found (see Pl. II), just west of Ely, to their eastern extension, where they abut against the Saganaga anticlinal area, occupy a synclinorium which trends approximately N. 70° E. and continues around the northern side of the Saganaga anticlinal area into Canada. This synclinorium is narrow in its western part and widens out toward the east. In that portion of the district where the sediments have a considerable width their continuity is interrupted by numerous anticlines of older rocks. Here and there a boss of granite which has been intruded through these sediments is found, the sediments wrapping around it. These areas also are anticlinal in structure. For the most part the various anticlinal areas are commonly outlined by conglomerates which lie on the flanks of anticlinal hills whose centers are occupied by an older rock. Where the sediments alone occur the conglomerates occupy the centers of the anticlinal areas. The bedding is so poorly preserved in the conglomerates as a rule that one can not get many strike and dip determinations to assist in interpreting the structure. Unquestionably these conglomerates must have been folded with the other sediments, although such folding can not be traced in detail on their exposures. It is shown, however, by the distribution of the slates, which dip away from such anticlinal areas of conglomerate. The slates invariably occur within the synclines, forming depressions as a result of their initial position at the bottom of the syncline and as a result of the relative ease with which they are eroded. This is shown, for example, in the broad area of slate surrounding Knife Lake. Exceedingly fine-grained, very cherty slates, breaking with conchoidal fracture, lie about in the axis of Knife Lake. As we go farther south from this point the sediments get coarser, graywackes gradually becoming associated with the slates, and finally the sediments grade into conglomerates. This same condition exists north of the lake, although there the conglomerates are not so greatly developed as to the south of it. Within this and other broad slate areas small slate anticlines very probably occur, for although no such anticlines have been clearly demonstrated to exist, indications of them have been found.

As is shown on the map, this broad area, underlain by the Lower Huronian sediments, is separated from several detached areas to the south by intervening highlands, occupied by the Ely greenstone and the Snowbank and Cacaquabic granites, named in order of age. In the area south of these highlands, formed of the older rocks, the structure of the sediments is totally different from that seen in the large area to the north. South of these anticlinal highlands the sediments occur in a southward-dipping monocline which extends with few interruptions from the vicinity of Snowbank Lake to the eastern end of the slate area on Paul Lake. There is a continuous narrow monocline of slate extending from Cacaquabic Lake east to Lake Gobbemichigamma, and lying between the high Twin Peaks anticline on the north and the gabbro on the south. This belt of rocks has been much metamorphosed by the gabbro.

The slates of the Lower Huronian show the effect of the pressure much better than do the conglomerates, and the remainder of the description of the structure of the sediments applies specifically to the slates forming the upper part of the series. In addition to the close folding, which is indicative of great pressure, the Lower Huronian Knife Lake slates have been jointed and faulted, and schistosity and cleavage have been produced. In general, the major joints have an east-northeast trend, and the cross joints have a trend not quite at right angles to the first. These joints make the slates break into rhomboidal blocks and are the chief cause of the formation of the high cliffs. The strike of the joints varies with the direction from which the pressure producing them came. Thus, in the western part of the area, where the pressure was apparently N. 10° W. to S. 10° E.—that is, perpendicularly to the axis of the folds and to the strike of the bedding—one set of joints trends about N. 80° E., and another trends in a direction very nearly at right angles to it, making an angle a little less than a right angle with the first set of joints. In the eastern part of the district, however, where the slates abut against the granite of Saganaga Lake and wrap around it, the direction of the joints changes. Thus in sec. 35, T. 66 N., R. 6 W., three sets of joints were noted. The first set strikes N. 25° E., and dips 30° to the northwest, corresponding closely with the strike of the schistosity. The second strikes N. 10° W. and dips 85° to the west. This agrees with the bedding. The third set strikes N. 60° E. and dips 85° to the southeast. The strike of these joints evidently influences very materially the shape of the lakes in this part of the district. For instance, in the case of the lake in secs. 34 and 35, T. 66 N., R. 6 W., these joints can be seen to determine the long direction of the lake and the trend of the bays.

In a few places we find that the slates show minor faulting along the joints. No cases were seen, however, where the throw was more than about 1 foot. South of Fox Lake, at a place north 1,915 paces, west 600 paces from the southeast corner of sec. 35, T. 65 N., R. 6 W., the interbedded slates and graywackes are broken and slightly faulted. The fault plane runs N. 10° W. The shearing accompanying the faulting has affected a zone about 3 feet wide. In the midst of this zone there is a horse of the country rock. Around it the material is sheared and brecciated, and the infiltration of silica has taken place subsequent to this shearing. The beds in the sediments on both sides of the fault have been bent. The amount of displacement could not be measured, but seems to have been slight—a very few feet at the most.

The schistosity and cleavage which have been produced are well marked on the slates. They show the variable relations to the bedding planes which are shown by Van Hise [a] to be consequent upon their mode of formation, and are clearly the result of the compressive forces which caused the folding. Thus they may be essentially parallel to the bedding on the flanks of the folds, and vary from this position to a position at right angles to it, near the apices of the folds. This cleavage can be well seen on the good exposures southwest and west of the portage from Moose into Flask Lake. South of Ogishke Muncie Lake, where the beds strike N. 25° to 30° W., the schistosity strikes N. 60° E. The difference in the behavior of the soft and hard beds—that is, the weak and the strong beds—under the same condition of pressure are well brought out at one place upon Ogishke Muncie Lake. At the southwest end of the long point projecting southwest into sec. 27, T. 65 N., R. 6 W., at the southwest end of Ogishke Muncie Lake, there are in the slate near the water's edge alternating bands of harder and softer materials. In the softer bands, cleavage running parallel to the bedding has been produced, while in the harder ones cross joints have been formed, running practically perpendicular to the cleavage in the soft beds. This difference is evidently due to the difference in the elastic strength of the two rocks. The one, the slate, practically flowed under pressure, while the other was fractured. The deformation evidently took place while these rocks were in the zone described as the combined zone of flowage and fracture.[b]

Excessive crumpling is very noticeable in the cherty layers and in the slates. This crumpling is especially well shown on the portage between Fox and Agamok lakes, and is illustrated in fig. 1, Pl. Y, Minnesota Geological Survey, Vol. IV. The bands here are fractured along planes

[a] Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Pt. I, 1896, pp. 573–874.

[b] Ibid.

which make angles somewhat less than a right angle with each other. The schistosity in the softer bands, produced as the result of shearing, is nicely shown in places on these sediments.

RELATIONS.

RELATIONS OF THE SEDIMENTARY MEMBERS OF THE SERIES TO ONE ANOTHER.

The relations of the Ogishke conglomerate, the iron-bearing Agawa formation, and the Knife Lake slates to one another is that of three conformable formations, with the Ogishke conglomerate at the base and the Knife Lake slate at the top. They occur constantly in this position, the iron-bearing formation being wanting at some places, but present at others. There are gradations between the formations. The lines which have been drawn are based upon the petrographic character of the rocks and the preponderance of the various kinds.

RELATIONS OF THE LOWER HURONIAN SEDIMENTS TO THE ADJACENT FORMATIONS.

RELATIONS TO THE ARCHEAN.

Relations to Ely greenstone.—The relations of the Lower Huronian sediments to the Archean greenstones are clearly shown at a number of places where the Ogishke conglomerate has been found in association with them. As a rule the conglomerate lies upon the flanks of the greenstone anticlines and is made up chiefly or solely of pebbles and bowlders which can be identified with the rocks constituting the Archean complex, so as to show unmistakably their source. Thus, for example, at a great number of places south of Moose Lake the conglomerate was observed in direct contact with the greenstones, which occur in conspicuous ridges forming the cores of the anticlines. In some places the conglomerate lies immediately adjacent to the fine-grained ellipsoidal greenstone, and at other places, where the ellipsoidal portions have been removed by erosion from the greenstone mass, the conglomerate lies against the coarse-grained greenstone which normally is at some distance from the border of the greenstone areas. Moreover, wherever finer-grained forms of the clastics showing bedding occur, it is usually found that this bedding is essentially parallel with the contact of the sediments and the underlying greenstones.

The contact of the Ogishke conglomerate with the greenstones was also observed on the north side of Twin Peaks ridge and the occurrence there was in general agreement with the description given by N. H. Winchell.[a] Furthermore, the contact was found between the conglomerate and the small ridge of greenstone which lies just along the south shore of Ogishke Muncie Lake, and a number of additional contacts were observed on the south side of the great anticline north and northeast of Gobbemichigamma Lake. The fragmental character of some of these deposits was recognized by the Minnesota survey, but it was not seen that they were sedimentary deposits of later age than the greenstone. They were, on the contrary, regarded as fragmental volcanic rocks, and were included, with the greenstone, in the Archean.[b]

Relations to the Soudan formation.—The actual contact between the conglomerate and the iron-bearing formation was observed at only one place. Here, however, the evidence is indisputably clear. The jasper of the Soudan formation is overlain by a conglomerate containing fragments of jasper derived from it as well as fragments of greenstone derived from the greenstones, which in their turn underlie the iron-bearing formation. In addition to this direct contact, where the evidence is perfectly clear, there have also been found at a number of places scattered all over the district quantities of jasper pebbles in the conglomerate. Their presence is sufficient, of course, to prove that the Soudan formation is older than these conglomerates.

The fragments of slate and of the conglomerate or breccia which occur in the Ogishke conglomerate south of Moose Lake are of especial interest, since they indicate the existence of a series of clastic sediments prior to the formation of the Ogishke conglomerate. The field evidence for such a clastic deposit below the normal iron-bearing formation has already been given. In this series there are slaty rocks associated with conglomeratic clastics. The fragments of slate and conglomerate may very well have been derived from these. In the conglomerate there were found a number of slate pebbles. Their source has not been very satisfactorily accounted for. If we accept the presence of certain sediments mentioned as lying in a position between the iron-bearing formation and the greenstone as indicative of the fragmental sedimentary horizon underlying the

[a] Geol. and Nat. Hist. Survey of Minnesota, Fifteenth Ann. Rept., 1886, pp. 372–374. Final Rept., Vol. IV, 1899, p. 451.

[b] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 466.

jaspers, then these slates are accounted for, as they occur in conglomerates younger than and containing fragments of the jasper. In a similar way the conglomerate or breccia pebbles observed can be accounted for. It should be noted, however, in connection with the explanation of the source of these pebbles, that we do not know whether they are true conglomerates or merely friction breccias, or pseudo-conglomerates. In the greenstone south of Moose Lake there were numerous small zones which had been so extremely fractured and then after the fracturing had been so sheared that in many cases friction breccias have been produced which closely resemble normal conglomerates and from which it would be perfectly possible to derive the pebbles seen in the overlying conglomerates were the breccias produced before the sediments were formed.

Relations to the granite of Saganaga Lake.—In the northeastern part of the district the Ogishke conglomerate is very close to the granite of Saganaga Lake and in several places contacts between these two rocks have been found and their relationships thereby made perfectly clear. In several places a great bowlder conglomerate has been found immediately overlying the granite of Saganaga Lake and consisting essentially of fragments of this granite. Detailed description has already been given of the field relations of the granite of Saganaga Lake to this conglomerate under the description of the granite (p. 271), and it was there shown that the idea held by Lawson that the granite of Saganaga Lake was intrusive in the conglomerate was untenable,[a] hence it will not be necessary to repeat this description here. From the evidence it is perfectly clear that the Ogishke conglomerate is younger than the granite of Saganaga Lake.

RELATIONS TO LOWER HURONIAN.

Relations to the Giants Range, Snowbank, and Cacaquabic granites, and various dikes of granite and granite-porphyry.—In the western portion of the Vermilion district there is found a conglomerate—correlated with the Ogishke conglomerate—which is in contact with the Giants Range granite, and has been penetrated by dikes from this granite. In the vicinity of Snowbank Lake a similar conglomerate practically surrounds the area underlain by the Snowbank granite, and in a great number of cases it has been found to have been penetrated by dikes from this granite. A portion of the area underlain by the Cacaquabic granite is likewise surrounded by

[a] Lake Superior stratigraphy, by A. C. Lawson: Am. Geologist, Vol. III, 1889, pp. 320–327.

the Ogishke conglomerate and, as in the preceding cases, the conglomerate is found to be penetrated by offshoots from this granite massive. At other places in the district, where the conglomerate is distant from the granite massive, it is cut by dikes of rhyolite-porphyries or granite-porphyries, or possibly of both. In all cases, however, the relationship is clearly that of intrusion, the conglomerates being intruded and metamorphosed by the granites. Hence the conclusion that the conglomerates are of greater age than the granites which penetrate them.

Relations to certain basic and intermediate dikes of Lower Huronian age.—At numerous places dikes of slightly varying character—altered basalts and lamprophyres—have been found cutting the Lower Huronian rocks. None of these dike rocks are found as dikes in the overlying Upper Huronian series. Hence they are believed to have been intruded in the Lower Huronian rocks at about the time when they were being folded and intruded by the aforementioned granites. Certainly some of the dikes are later than some of the granites, as they are found cutting the granites.

RELATIONS TO THE UPPER HURONIAN SERIES.

It was found that the most difficult problem of relation to be solved was that of the relationship between those rocks which are here classed as the Lower Huronian (consisting of the Ogishke conglomerate, the Agawa formation, and the Knife Lake slates) and the Upper Huronian (Animikie) rocks. These rocks come closest together in the vicinity of Gobbemichigamma Lake, and here, if at all, their relations were to be determined. A considerable time was therefore spent in the study of the rocks in this vicinity. Unfortunately where the rocks of the series come closest together the Lower Huronian is represented by conglomerates which give no good strikes and dips, and the Animikie is represented by the metamorphosed iron formation which lies at its base in this district.

In the area referred to the Lower Huronian rocks are extremely folded, and where this series is in contact with the Animikie, the vertical or very steeply dipping rocks of the Lower Huronian were found to strike in such a direction on the east side of Gobbemichigamma Lake as to bring them very nearly at right angles against the Animikie, which has a very low dip to the south, with a strike slightly north of east. Only in two places were the Ogishke conglomerate of the Lower Huronian and the iron-bearing formation of the Upper Huronian series observed in contact, and in both places there is a very striking difference in the lithologic character of the two rocks. The iron-bearing formation is made up essentially of beds of magnetite alternating with very quartzose bands, whereas the conglomerate is the normal greenstone conglomerate, although very much altered. There is no transition between the two, and the relationships appear to be those of two unconformable series of rocks. The evidence of this unconformity is, however, not absolutely conclusive in the Vermilion district. The opinion of the majority of those who were studying these rocks for the Survey was in favor of this unconformable relationship, and in this respect was in thorough agreement with the conclusions reached and already published by the Minnesota survey. However, in view of the fact that some of the rocks were intensely plicated, it was recognized that it was possible for them to change both their strike and dip within a very short distance, even within the distance which separated them from the Animikie and in which there were no exposures. Such a change might possibly bring them into perfect conformity with the Animikie. In view of this possibility we could not all agree to accept the unconformable relationship as proved. In 1900, shortly after work was begun in the Mesabi, Mr. C. K. Leith had the good fortune to find a place where the relationship between these two series is unmistakably shown.[a] At this point, north of Biwabik, the vertical Lower Huronian beds were found overlain by the low southward-dipping rocks of the Upper Huronian series, with a thin basal conglomerate at the bottom. The correctness of the opinions previously held were thus demonstrated beyond all doubt.

RELATIONS TO THE KEWEENAWAN.

Relations to the Keweenawan gabbro.—In Ts. 63 and 64 N., Rs. 8 and 9 W., the Ogishke conglomerates and Knife Lake slates are found in many places almost in juxtaposition with the Duluth gabbro mass of Minnesota. In no cases were actual contacts observed between them, as invariably a topographic depression, occupied either merely by lower ground or, as in most cases, by water, intervened. The Keweenawan gabbro has been long recognized as one of the youngest rocks occurring in Minnesota. Where the conglomerates and gabbro are in contact the gabbro has been found to metamorphose the conglomerates and slates very extensively, and hence

[a] Mon. U. S. Geol. Survey Vol. XLIII, 1903, p. 181.

the conclusion is unavoidable that the gabbro is very much younger than the Ogishke conglomerate and Knife Lake slates.

Relations to basic dikes.—Cutting through the Ogishke conglomerate and Knife Lake slates at various places, basic dikes of the character of dolerites have been observed. These dikes are of exactly the same nature as those which are found cutting through the gabbro which represents the youngest member of the series in the Vermilion district, excluding, of course, as was done in the statement at the beginning of this monograph, the glacial deposits. Since the dikes in the conglomerate are lithologically the same as those cutting the gabbro, they are assumed to be of the same age, although direct relationship between the dikes in the conglomerate and slates and those in the gabbro have never been observed.

AGE OF THE LOWER HURONIAN SEDIMENTS.

The descriptions given in the above paragraphs of the relations existing between the conglomerates and slates of the Lower Huronian and the adjacent formations throughout the district enable us to make with confidence the following summary statement concerning the relative stratigraphic position of these sediments in the Vermilion district. Since they lie unconformably above the rocks of Archean age, they must of necessity be younger than the Archean rocks. They are older than the Snowbank, Cacaquabic, and Giants Range granites, which cut and metamorphose them, and older than some basic dikes which are intrusive in them. The chief interest, however, is in their relationship to the Animikie sediments, which are very generally recognized as being of Upper Huronian age. The sediments here classed as Lower Huronian are unmistakably of an older period of formation than these Animikie sediments, since these Animikie sediments rest unconformably upon them, as is shown by the relations observed in the adjacent Mesabi district. Hence the three conformable formations, the Ogishke conglomerate, the Agawa formation, and the Knife Lake slates form one series of rocks of Lower Huronian age. In the eastern part of the Vermilion district these sediments bear the same relations to the adjacent formations as in the western part. They lie at the base of the Algonkian sediments, and rest unconformably upon the Archean rocks, and are correlated with the Lower Huronian series of the rest of the Lake Superior region.

OGISHKE CONGLOMERATE.

PETROGRAPHIC CHARACTERS.

Macroscopic characters.—The Ogishke conglomerate varies from a coarse bowlder conglomerate with bowlders up to 20 inches in diameter, as shown on the southwest side of Cache Bay of Saganaga Lake, down through all intermediate gradations of coarseness into rocks which are designated as grits, and through these into slates. The grits are, of course, interbedded with the conglomerates, but no attempt has been made to separate them from the conglomerates on the maps where it was recognized that they occurred in very subordinate quantity. The conglomerates contain a great variety of pebbles. We find among these a great number of kinds of altered basic eruptives, both massive and schistose, coarse and fine grained, porphyritic and nonporphyritic, amygdaloidal and nonamygdaloidal, some showing flowage lines produced by parallelism of the feldspars, and others with spherulitic structure. Among the most striking of these are the porphyritic rocks in which the feldspar and hornblende are the phenocrysts and occur either alone or together. Upon one ledge seven different kinds of greenstones were counted. The granites which occur in pebbles and bowlders in the conglomerates show varieties ranging from coarse and fine evenly grained to porphyritic and nonporphyritic forms. There are several kinds of fine-grained acid porphyries also. A few slate fragments and two fragments of a conglomerate were likewise seen in the coarse clastics. Black and gray chert, jasper, vein quartz, and a number of fine-grained gray pebbles, whose characters were undetermined, occur associated with those mentioned.

The brilliant red-jasper fragments lying in the green matrix give the conglomerate a very handsome appearance. With this jasper-bearing conglomerate, and a phase grading over into the Knife Lake slates, there occurs a dark-green medium-grained graywacke with a faint speckling, due to the small, bright-red fragments of jasper scattered through it. The amount of small jasper fragments varies in quantity, being rare in some cases, and in others so numerous as to influence very markedly the color of the graywacke.

Many of the jasper fragments which occur in this conglomerate possess a well-developed zonal structure. The centers of the fragments are red and the peripheries are black, producing a very striking appearance. This zonal structure, moreover, is parallel to the irregular contours of the pebbles. The alteration is evidently due to the reduction of the iron oxide (Fe_2O_3=hematite) to magnetite (Fe_2O_3 FeO). The zonal structure in these fragments is very good, and must have been formed after the jasper had acquired its present fragmentary character, as the zones run parallel with the irregular margins of these fragments. Some of the fragments are a foot long, although the majority of them are only a few inches in diameter. Where there is brilliant red jasper lying near the conglomerates it is natural to look for some iron-bearing formation as the local source of the pebbles. However, a great deal of the conglomerate occurring upon and in the vicinity of Ogishke Muncie Lake has as its most striking constituent brilliant-red jasper pebbles, and yet there is no known typical iron-bearing formation nearer than that which occurs on Otter Track Lake, 5 miles away to the northwest. The intervening area is underlain by finer sediments—graywackes and slates for the most part. The brilliant jasper from this vicinity is in its general character similar to that of Lower Huronian age which occurs at Soudan, Ely, and other places in the district. It seems scarcely reasonable to derive these pebbles from a source so far distant as the exposure on Otter Track Lake, especially as the jasper occurs in such large quantity in the sediments exposed in the area extending approximately from West Gull Lake southwestward to Cacaquabic Lake. Winchell[a] reports the occurrence of a small quantity of jasper upon Townline Lake, but search failed to reveal it. Moreover, the Archean area to the south and east of these sediments has been hunted over for the Soudan formation, which it was supposed might be lying in troughs within it, but it was not found. The Soudan formation, if it ever existed in this area, and it is highly probable that it did exist, has been deeply buried under the sediments or completely removed by erosion. The probability of such a removal will be seen to be great when we consider the enormous thickness of sediments which lie west and northwest of the Archean and which consequently indicate a long period of erosion and deposition.

The matrix of the Ogishke conglomerate is the finely triturated material derived from the various rocks which have been mentioned as occurring in pebbles in the conglomerate.

[a] Geol. and Nat. Hist. Survey of Minnesota, Sixteenth Ann. Rept., 1885, p. 315.

The proportion of the different kinds of pebbles varies greatly, and consequently we find conglomerates of very different chemical and physical aspects. The dependence of the character of the conglomerate on the petrographic nature of the adjacent rocks from which it has been derived is well illustrated as we follow northward the line of contact between the granite of Saganaga Lake and Ogishke conglomerate on Cache Bay of Saganaga Lake, where we get the Ogishke conglomerate in contact with the Ely greenstone, which has been cut by numerous dikes of the granite of Saganaga Lake. As we go in this direction we find that the basal conglomerate contains occasionally fragments of greenstone, and these become more and more numerous, the granite appearing in proportionally smaller quantity as the area in which the greenstone occurs is approached. Finally, when we get well within the area in which the greenstone occurs, the conglomerate is made up chiefly of greenstone fragments, the matrix likewise being detrital material from the greenstone with only an occasional granite pebble, derived probably from the granite dikes which traverse the greenstone or possibly transported from the main granite area. The changeable character of the basal conglomerate within a very limited area, its character depending on the petrographic nature of the surrounding rocks, is also seen here, as above described, and shows the uncertainty of correlations which depend on the similarity of the lithologic character of sedimentary deposits occurring in widely separated areas. The differences in the Ogishke conglomerate at various localities is clearly due to the varying character of the immediately adjacent rocks from which the conglomerates have been derived. This is shown at a number of places. Thus in some conglomerates all of the pebbles are greenstone, and the matrix is likewise made up of the dust from these greenstones, so that the resulting rock is green, with pebbles showing various textures, such as occur in basic rocks. Jasper occurs in numerous fragments in these rocks, and their brilliant color offers a very striking contrast to the usual monotonous green of the conglomerates. Here and there a pebble or bowlder of granite will appear, and again there may be an approximately even mixture of pebbles of granite and greenstone. In other places the fragments of granite are present in such quantity that they are the predominant bowlders. In such places the matrix likewise is found to have changed from the green of the greenstone conglomerates to the gray or pinkish color characteristic of granite débris. The most noticeable differences in the appearance of the Ogishke conglomerate are between those varieties which are made up almost exclusively of greenstone, which are therefore green in color, and those in which the granite bowlders form the greater portion, such varieties having a gray to reddish color on weathered surfaces. Between these there are, of course, all gradations. In general the gray, bluish- to greenish-gray, slate-colored, and green-colored rocks predominate. These different kinds of conglomerates were noted before they were all correlated, and, for convenience, the conglomerate made up essentially of greenstone pebbles, which is so typically developed in the vicinity of Moose Lake, was spoken of as the greenstone conglomerate. These greenstone conglomerates were for a while rather puzzling, as it was not easy to determine whether they were volcanic tuffs or true sedimentary rocks, in the one case contemporaneous with and in the other older than the greenstones with which they were associated. Grant, after having studied the district, reached the conclusion that the clastic rocks on the south flank of the Archean tongue lying south of Gull Lake and extending thence eastward were tuffs derived from these greenstones.[a] Field work having for its object the determination of this particular point has been carried on, and as a result sufficient indications of the sedimentary origin of the clastics have been found to justify their classification as conglomerates. Moreover, in numerous other places elsewhere in the district, interbedding of the finely bedded sediments with these conglomerates and gradations between them have been observed, so that there can be absolutely no doubt that they are normal sediments. The conglomerate at Ogishke Muncie Lake contains pebbles of greenstone, granite, jasper, and other varieties of rocks, and is the normal basal conglomerate of the Lower Huronian for the eastern part of the Vermilion district.

Microscopic characters.—A certain amount of microscopic study was made of the conglomerates. This consisted primarily in the determination of the characters of the pebbles and of the matrix. In addition to the constituents recognizable macroscopically, which have already been enumerated, the microscope discloses the presence of fragments of basaltic lavas with various microscopically recognizable textures, spherulitic rhyolite, rhyolite-porphyry, pieces of quartz and feldspar in pegmatitic intergrowth

---

[a] Geology of the eastern end of the Mesabi iron range in Minnesota, by U. S. Grant: Engineers' Yearbook, University of Minnesota, 1898, p. 54.

(presumably derived from pegmatitic granites), round to subangular grains of cloudy feldspar, quartz, ragged pieces of biotite altering to chlorite, green hornblende, augite, apatite, zircon, and a large amount of fine indeterminable interstitial material derived from the trituration of the various materials already mentioned. From the decomposition of this interstitial material, as well as from the associated larger fragments, there has been produced the secondary minerals chlorite, calcite, actinolite, sericite, epidote, quartz, feldspar, and pyrite, which occur in large quantity in the sediments. The prevailing green tones of the sediments is especially due to the very large quantity of the green hornblende, epidote, chlorite, augite, and sericite which is present. In a few cases the well-bedded graywackes associated with the conglomerates, and especially those near the conglomerates that are composed chiefly of greenstone fragments, are found to consist very largely of fragments of crystals of hornblende, augite, and feldspar, with an occasionally well-preserved entire crystal. Such sediments resemble the crystalline tuffs of volcanic origin. The beautiful bedding and association with other sediments show clearly that these rocks are water-deposited sediments.

METAMORPHISM OF THE OGISHKE CONGLOMERATE.

It should be borne in mind that the conglomerates thus far described are by no means in their original condition, but have been extensively metamorphosed. This metamorphism has been that produced chiefly by cementation, due largely to infiltration of silica and some calcium carbonate and chemical change of the constituents producing new minerals, and also secondary enlargements of the old minerals. As the result of these changes and additions the conglomerates have been thoroughly indurated. This is the widespread metamorphism which is common throughout all of these Lower Huronian sediments. The kinds of metamorphism now to be described are exceptional; they are not those most common in these conglomerates.

The Ogishke conglomerate has been metamorphosed both as the result of orogenic movements and in consequence of the intrusion through it of various granites, as well as of its contact with the Duluth gabbro of Keweenawan age. The result of crustal movements is well shown in the schistose conglomerate which may be seen at the easternmost point south of the channel between Birch Lake and Sucker Lake. Here the conglomerate consists almost exclusively of fragments of the greenstone which lies on the north side of the channel. An occasional fragment of vein quartz is present. This rock has been so extremely mashed that the pebbles have been rolled out and flattened, and it is now fairly difficult to recognize its true character. Its fragmental character is best shown on the portions of the exposure where one gets sections transverse to the direction of greatest flattening in the pebbles. The difficulty here is increased by the fact that, as stated above, the conglomerate consists almost exclusively of the greenstone, the matrix, of course, being derived from the same source and consisting of the same material.

A mashed conglomerate similar to this in every respect was seen at a number of places on the very irregular stream that connects Cache Bay of Saganaga Lake with Saganagons Lake in Canada. The best place at which to see this conglomerate is on the south shore of the stream where it turns northeastward and flows into the southwest bay of Saganagons Lake. In this vicinity the greenstone and the overlying sediments have been very closely infolded, and as a result of the folding excessive shearing has taken place along the limbs of the folds. Here, again, if the conglomerate is viewed transversely to the bedding, its nature can be readily recognized. On some of the cliffs, however, which run parallel with the bedding of the conglomerate, and essentially with that of the schistosity, the conglomeratic nature is not so readily recognized. The pebbles occasionally stand out as more or less rounded patches on the cliff face, but very commonly blend with the matrix so nicely that the rock appears almost homogeneous.

Naturally where the conglomerate is made up of a great variety of pebbles, its true character may be recognized with greater ease than in the above-mentioned instances. Usually where the conglomerate has been folded, the pebbles have not been much affected. The conglomerate may in general have a schistose character, and this schistosity usually agrees, approximately, with the long direction of the pebbles. Closely examined, it will be found that the pebbles themselves are in most instances not even fractured, but preserve their original shape perfectly. Pebbles of granite have been obtained from this conglomerate which were as symmetrical in shape and apparently, to the naked eye, as fresh in character as pebbles obtained from a modern shingle beach of Lake Superior. The pressure on the conglomerate has been relieved by movement in the matrix, and this matrix has in most cases been rendered perfectly schistose. It will be found that the schistosity, when it approaches a pebble, gradually bends so as to run around the ends of the pebble, and then upon the flat sides continues in its normal direction.

The contact metamorphism resulting from the intrusion of igneous rocks seems to have been more far reaching in its character—at least so far as it has produced changes in the petrographic character of the conglomerate—than the metamorphism due simply to orogenic movement. In all probability the action of the intrusives is complicated by the fact that their intrusion took place subsequent to some orogenic movements, so that they acted on rocks which had already been somewhat metamorphosed. The best area in which to study this contact action is in the vicinity of Snowbank Lake. Snowbank Lake lies in a granite massive, which has received its name, the Snowbank granite, from the lake. The Ogishke conglomerate surrounds this lake and is exposed with bare surfaces over large areas. At a considerable distance away from the lake the conglomerate possesses its normal characters, but as the lake is approached it will be seen that gradually it changes. This change is for the most part a petrographic one, and has consisted of the production of micaceous and hornblendic schists from the finer-grained sediments associated with the conglomerates and from the fine matrix between the pebbles of the conglomerates. The pebbles in the conglomerates have also been altered, certain kinds, of course, very much more than others. In general these finer materials are now well-developed mica-schists in which the conglomeratic character can, however, be readily recognized by the presence of comparatively unaltered granite pebbles. This alteration has reached its extreme where the conglomerates are nearest to the granite.

Long after the intrusion of the granite and the metamorphism of the conglomerates, the Keweenawan gabbro was intruded, and it has in turn modified the conglomerates, which were already metamorphosed by orogenic movements and by the granite. The effect of the contact action of the gabbro has extended for a considerable distance from the present exposures of the gabbro. The exact distance can not be determined with certainty, as its metamorphism blends with that produced by the granite. Possibly a more detailed field and petrographic study than was warranted in the present case might enable a boundary line to be drawn between the conglomerates metamorphosed by the granite only and those metamorphosed by both the granite and gabbro. The effect of the gabbro seems to have extended at least as far north as the northwest shore of Disappointment Lake. Reference has already been made to the beautiful exposures of conglomerate at this place. The matrix of this conglomerate contains biotite and hornblende very abundantly, and the pebbles and bowlders of the conglomerate are to a great extent of a hornblendic rock in which in many places large porphyritic hornblendes have been produced. On the weathered surface the pebbles generally decay faster than the matrix, and hence are removed, leaving numerous roundish depressions. The rock has not been very strongly mashed, for while the longer dimensions of the pebbles are in the planes of schistosity, one could not say that the lesser dimension in the other direction is not explicable as due to the original shingling action of the pebbles. The rock is very irregularly veined by quartz, and here and there by some granitic veins derived from the Snowbank granite. All these factors give the rock a very rough, knotty appearance on the weathered surface. While in general the outlines of the pebbles can be readily traced, nevertheless, when they are broken the fractures extend cleanly through the pebbles and matrix alike. This shows the close union between the matrix and the pebbles which has taken place as the result of metamorphism. This is further shown by the fact that in some cases secondary porphyritic hornblendes, which are produced in certain of the pebbles and in the matrix alike, will be found to extend from the pebble across the contact into the matrix. As we go southward—in other words, as we get closer to the gabbro—a study of the rocks on the small islands in Disappointment Lake and on the south shore shows that the clastic nature of the rocks is not so apparent here. A microscopic study of these rocks shows that there have been produced in them in large quantity minerals—hypersthene, green and brown hornblende, brown mica, augite, magnetite—whose origin is clearly due to the action of the gabbro.

Similar rocks may be studied in the area extending from the north shore of the Kawishiwi River in secs. 16, 17, and 20, T. 63 N., R. 9 W., near the shore. They are extremely metamorphosed and it is only by rather close observation that one can recognize their conglomeratic nature. The pebbles and the matrix of the rocks consist to a great extent of the same material, and as the result of the metamorphism essentially the same new minerals have been produced in them, and this production of new minerals has tended to render the characters of the rock more uniform. It is only here and there, where a pebble occurs, whose mineral composition was not so extremely changed by the metamorphism that the conglomeratic character of the rock can be distinctly recognized. In such cases these pebbles seem to withstand the weathering better than does the adjacent material in which have been produced, as above stated, the basic minerals associated with the gabbro. This portion of the rock weathers more readily than the less affected pebbles which stand out from the rest of the rock and show their true pebble characters.

THICKNESS OF OGISHKE CONGLOMERATE.

No data have been obtained that would enable us to make an accurate determination of the thickness of the conglomerate. In places it is wanting or is represented by a few feet of rock at most, and from this it runs up to a thickness of possibly a thousand or more feet.

INTERESTING LOCALITIES.

The portage between Moose and Flask lakes is a good place at which to study the Ogishke conglomerate as developed south of Moose Lake. A short distance east of the portage landing on Moose Lake as the hill is ascended we find slates similar to those occurring along the east shore, which appear to grade into a fine conglomerate and then into a coarse conglomerate which crowns the brow of the hill. The rocks along this gradation zone are much mashed, so that one can not be certain that the change is due to actual continuous sediments differing only in coarseness. The conglomerate is very coarse at this place, having bowlders up to 2½ feet in diameter. The fragments in the conglomerate are of many different rocks—various kinds of porphyries, granites, many different varieties of greenstone, jasper, an occasional slate fragment, and two fragments of a conglomeratic or brecciated rock, the fragments and matrix in these two pieces being very much alike, and apparently both derived from greenstone. Still farther along the trail the same conglomerate occurs at numerous places, and here and there are exposures of much contorted slates associated with the conglomerates. Some dikes of granite-porphyry with large quartz phenocrysts may also be observed cutting the older sediments. After leaving Flask Lake one finds, in traversing the portage between Flask Lake and Snowbank Lake, a number of good exposures showing a rather coarse greenstone conglomerate, which is well developed in this vicinity. These conglomerates very rarely contain any pebbles of granite or jasper, most of the fragments being of greenstone, and in this respect the conglomerates are different from those occurring farther north and west, nearer Moose Lake. They have also suffered more from metamorphism, since they are nearer to the main Snowbank granite massive which has intruded them.

The northwest shores of Disappointment Lake afford the best places in the Vermilion district for studying the Ogishke conglomerate. At the time of the survey here reported the country had been recently burned over and the hills were practically bare. There was a little scanty vegetation, but one could see bare rock exposed in great flat or slightly rounded surfaces nearly everywhere. Great beds of coarse bowlder conglomerates were exposed, grading into finer-grained conglomerates, and these through graywackes into slates, to be succeeded by a repetition of these gradations. The strike of the bedding is very uniformly N. 20° W., the dip varies from 75° west to 80° east, but is very commonly nearly vertical. The conglomerate at Disappointment Lake differs from the typical Ogishke in respect to the absence from it of the jasper which is so common in the typical Ogishke. No pebbles of this kind were found on Disappointment Lake. The pebbles consisted chiefly of varieties of granite and porphyry, and especially of numerous varieties of greenstone. In fact, many of the beds of conglomerate consisted exclusively of pebbles of different varieties of greenstone, and the matrix between the pebbles consisted of finer detrital matter derived from the same source. The conglomerates had been intruded by a number of dikes, basic as well as acid, and they had been metamorphosed by the Snowbank granite, from which the granite dikes are offshoots, and subsequent to this metamorphism had been further metamorphosed by the great Keweenawan gabbro. Consequently the nearer one approaches the Snowbank granite the greater the metamorphism, and the changed character of the sediments is still further increased as one goes along the margin of the granite mass and approaches nearer to the gabbro. In some places, even at considerable distances from both of these intrusive rocks, the conglomerates have been so much altered that their true characters could be detected only on careful examination. The greater the variety of pebbles the more difficult it becomes to conceal the true character of the conglomerate, as even in the most extreme cases it is probable that some one or more of the kinds of pebbles may retain very nearly their normal characters. But when, as was frequently found to be true, the conglomerate beds are made up essentially of one kind of rock, the greenstone, and when this has been metamorphosed, it is found that it is sometimes difficult to recognize the original character. In fact, in such a case as this large secondary hornblende crystals were found to have been produced throughout the conglomerate, and in the matrix as well as in the pebbles, and likewise grew from the pebbles out into the matrix.

From Disappointment Lake north to the vicinity of Ensign Lake, and from Ensign Lake east to Lake Cacaquabic, there are a number of areas outlined on the map (Pl. II), in which the Ogishke conglomerate is exposed. In all of these areas the conglomerate consists essentially of greenstone pebbles, with granite pebbles secondary in abundance. Jasper is practically wanting. In general appearance the conglomerate is green as the result of the preponderance of the greenstone, and since the brilliant-red jasper pebbles are wanting it does not present the appearance of the typical Ogishke conglomerate. On the north shore of Cacaquabic Lake the Ogishke conglomerate is also exposed. Here the greenstone is practically the only kind of pebble in the rock, and the conglomerate is very similar to some of the greenstone tuffs of other districts of Lake Superior. It was while studying this rock that Van Hise[a] observed the secondary enlargement of hornblende fragments. On the south shore of the long east arm of Cacaquabic Lake the normal Ogishke conglomerate is exposed here and there, and shows its typical characters especially well at the foot of the high cliff about half a mile east of the main body of the lake. Here, especially on the bowlders which lie just a few inches or feet below the surface of the water, the jasper pebbles, with their brilliant red color, stand out conspicuously. The granite pebbles increase in quantity and, as above stated, the rock is the typical Ogishke conglomerate.

At the narrows of the lake at the center of sec. 28, T. 65 N., R. 6 W., is a phase of the Ogishke conglomerate different from those heretofore

[a] Am. Jour. Sci., 3d series, Vol. XXX, 1885, pp. 231–235.

described. This is made up exclusively of both pebbles and matrix of granite débris. The matrix contains many subangular individuals of feldspar, derived in all probability from a porphyritic granite or feldspar-porphyry. In some places the fine graywacke, with the porphyritic feldspars which are associated with the conglomerates, simulates very much a feldspathic porphyry. East of this lake are here and there exposures of Ogishke conglomerate, usually in rather thin beds, associated with graywackes and slates. About a quarter of a mile south of the small lake just west of Ogishke Muncie Lake, the Ogishke conglomerate is again exposed in large masses with jasper pebbles present in great abundance. This conglomerate extends eastward to the lake and along its south shore, and eventually is connected with the great mass of conglomerate to the east of Ogishke Muncie Lake. As we go from the west end of the lake eastward, the jasper pebbles rapidly diminish in quantity, and eventually disappear, so that the conglomerate exposed on the south side of Ogishke Muncie Lake is made up chiefly of pebbles of different varieties of greenstone, with an occasional feldspathic porphyry and granite-porphyry pebble. The typical Ogishke conglomerate also occurs north of the west end of Ogishke Muncie Lake and is likewise exposed along the greater portion of the north shore of the lake. Here it is in all cases the typical jasper-bearing Ogishke, and this may be followed over the areas outlined on the maps and traced with almost continuous exposures through to West Gull Lake. It will be noted that we have here the two phases of Ogishke conglomerate—that known as the typical form, consisting of striking red jasper pebbles with large quantities of granite and greenstone, and that variety which consists essentially of greenstone pebbles with no jasper pebbles and only a few granite pebbles—separated from each other by the width of the lake—about half a mile. Between these lies a syncline of the Knife Lake slates. As these phases of the conglomerate are followed to the east the distance between them gradually increases, a headland consisting of Ely greenstone and granite of Saganaga Lake coming in between. These conglomerates are evidently the same. The difference in petrographic character can be readily explained as due to a difference in the underlying rocks from which they were derived. North of the headland of Ely greenstone and granite of Saganaga Lake the conglomerate consists, to a great extent, of pebbles of granite derived from the granite of

Saganaga Lake and pebbles of greenstone and jasper. The jasper evidently was derived from masses of the Soudan formation which were presumably infolded in the Ely greenstone. This was not present in large quantity and is now buried under the sediments, or, as the result of erosion, it has all been removed and is now found only as pebbles in these sediments; at least no masses in situ have thus far been found. South of the above-mentioned headland, where the conglomerate derived from the Ely greenstone is penetrated by an occasional dike of the Saganaga granite, we find that the pebbles are predominantly greenstone with only an occasional granite pebble. Jasper is also wanting here. As we follow these two belts westward they come closer and closer together, and petrographically they also approach more nearly to each other as the result of the intermingling of the granite pebbles and jasper pebbles, until, by the time we reach the first-mentioned area at the west end of the lake, the two conglomerates are close together and are petrographically the same. Clearly this was the place where the currents mingled the débris derived from the granite on the north side and the greenstone on the south side of this great westward-projecting headland.

The relations of the conglomerate to the underlying rocks are clearly shown by the fact that they consist of pebbles from these underlying rocks, and this relationship can be seen at a number of locations, to which reference has already been made in preceding pages (p. 268 et seq.). The conglomerates have been found in actual contact with the greenstone and with the granite, so that there can be absolutely no doubt as to their actual relationship. Such a conglomerate, lying between the Knife Lake slates and the great greenstone mass forming the Twin Peaks range south of Ogishke Muncie Lake, was described by N. H. Winchell.[a]

The location of this conglomerate could not be determined from Winchell's statement, but the contact along this range was followed out for a long distance. In many places the slates were found in contact with the greenstone. Where these first contacts were found the greenstone was schistose, and no distinct conglomerate was observed. Eventually, however, on the east slope of the prominent northward-trending hill of this greenstone, at a point 840 paces south and 650 paces east of the meander corner between secs. 27 and 26, T. 65 N., R. 6 W., the greenstone

[a] Geol. and Nat. Hist. Survey of Minnesota, Fifteenth Ann. Rept., 1886, pp. 372-374.

is found with about 9 feet of a conglomerate derived from it overlying it. Above this follow well-banded slates and graywackes. At another point, 875 paces south and 700 east of the same location, is another contact between the greenstone and the sediments. Here we find a band of conglomerate formed of poorly rounded greenstone pebbles which grades up by rapid alternation of conglomerate beds with finer-grained sediments into the normal Knife Lake slates. The bands of fine-grained conglomerate vary in thickness from a few inches to 3 feet, the thinner ones alternating with bands of the slates. The entire gradation here takes place within a distance of about 10 paces from the greenstone on one side to the normal slates, without marked conglomerate bands, on the other. The strike of the beds here is N. 60° W., with a dip of 80° to the north. As may be seen from the map, the strike follows very closely the outcrop of the greenstone.

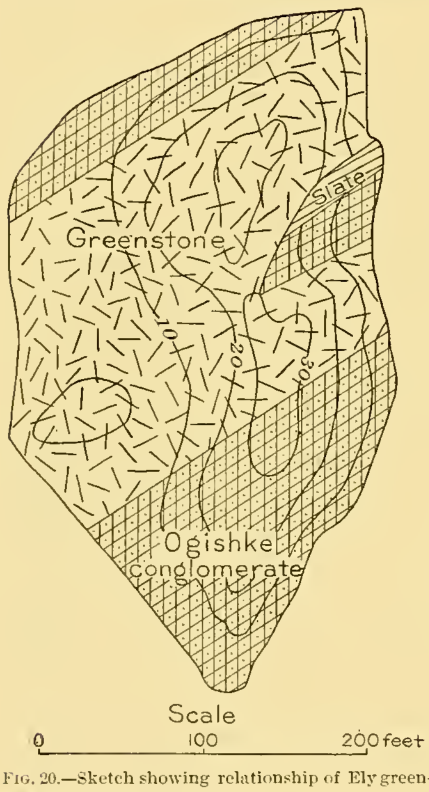


FIG. 20.—Sketch showing relationship of Ely greenstone and overlying Ogishke conglomerate on island in Ogishke Muncie Lake.

On the northern slope of the greenstone ridge which forms a subordinate anticline at the southwest end of Ogishke Muncie Lake, another contact was found between the Ogishke conglomerate and the greenstone. The contact occurs on the hillside at a place 225 paces south and 20 paces west of a point on the shore opposite and just south of the west end of the westernmost island shown on the map (Pl. XVI, atlas). The conglomerate here is fine grained and consists of greenstone pebbles with occasional jasper pebbles. The conglomerate is coarsest near the eruptive greenstone and grows progressively finer northward, evidently grading upward into the slates that occupy the central portion of Ogishke Muncie Lake.

The large island northeast of the east end of this same greenstone anticline well deserves examination, as it shows the relations of the greenstone and the conglomerate. The large-scale sketch (fig. 20) shows the distribution of the rocks. The conglomerate occurs both north and south of the greenstone, but on the east side of the island near the top of the hill there is a small area of slate and conglomerate which is clearly a part of the Ogishke conglomerate that was infolded in the underlying greenstone and has not been completely removed by erosion.

When this greenstone anticline which occurs at the southwest end of Ogishke Muncie Lake and also on the island just described is followed eastward along the south side of the lake, it is found to disappear for a distance of about one-third of a mile, it having plunged down under the conglomerate, which has not been eroded deep enough to show the greenstone. It reappears again near the north-south section line between secs. 27 and 26, T. 65 N., R. 6 W. Here the conglomerate is found in contact with the greenstone on the north slope, and extends north of the greenstone over a considerable area to the lake shore. South of the greenstone, however, no conglomerate was found. Near the west end of this anticline the slates seem to come in almost immediately. The actual contact between the two was wanting, and a thin conglomerate may occur in the depression between the two. This same greenstone anticline continues eastward and comes out again on the west side of the bay of Ogishke Muncie, into which empties the stream which comes from Fox, Agamok, and Gobbemichigamma lakes. Conglomerate is here again exposed all along the north side of the anticline, whereas on the south side the slates come up very nearly in contact with the greenstone. This southern edge of the greenstone was here followed for a considerable distance, in search of an actual contact between the greenstone and sediments, and at one place, just before the greenstone exposures cease and where a swampy area begins, a small patch of conglomerate was found hanging on the south face of the greenstone. The conglomerate here must be very thin, as the slates begin again a few feet south of the face of the greenstone ledge. If the map (atlas, Pl. XVI) is referred to it will be noted that south of these small greenstone anticlines bordering the south shore of Ogishke Muncie Lake there occurs a broad area of the Knife Lake slates which continue south to the great Twin Peaks greenstone anticline. The presence of this great breadth of slates between these anticlines, and the fact that where they are in contact with the greenstone there is but a very thin mass of conglomerate, indicate that during Lower

Huronian time this area was occupied by a comparatively protected sea, in which wave and current action was not very strong, and in which the slates were deposited with very subordinate masses of conglomerate.

On the south slope of the great greenstone anticline lying south of West Gull Lake and Gull Lake contact between the greenstone and the conglomerate derived from it can be found almost anywhere if one follows the boundary line closely. The conglomerate is in most places, however, so coarse that sedimentary banding is comparatively rare, and this may account for Grant's error in considering it a volcanic tuff.[a] The conglomerate here is exposed over an area about $1\frac{3}{4}$ miles wide, and this great width, as well as the coarseness of the conglomerate is evidence of its great thickness at this place. Moreover, where bedding is shown, for instance, on the hill 725 paces north of the northeast bay of Paul Lake, the beds are found to dip very steeply to the north. Clearly this greenstone was the shore of a great headland which was exposed to violent wave action, for otherwise such a coarse and thick conglomerate would not have been formed. The same statement is true for the great conglomerate which occurs to the north of this headland, and which consists to a great extent of granite derived from the granite of Saganaga Lake, although here the conglomerate is not so thick as that south of the headland.

THE AGAWA FORMATION (IRON-BEARING).

DISTRIBUTION AND EXPOSURES.

At several places in the eastern part of the Vermilion district there is found a carbonate-bearing and jaspery iron-bearing formation which is very intimately associated with the Knife Lake slates and is really but a phase of these. This formation occurs in widely separated areas, and in each instance it is exposed in comparatively small masses; consequently it is not possible to assert with perfect confidence that all of these ferruginous rocks belong to exactly the same horizon, although we are sure that they are very nearly contemporaneous. The areas in which it occurs in the United States are so small that we can state confidently that it will never be of economic importance. The formation is, however, very much more extensively developed in portions of Ontario adjacent to the Vermilion district of Minnesota, and

[a] Geology of the eastern end of the Mesabi iron range in Minnesota, by U. S. Grant: Engineers' Yearbook, University of Minnesota, 1898, p. 54.

it may be that ore deposits will eventually be found in this area, although it is very doubtful whether the formation carries ore in paying quantity at any of the places examined. The greater part of the data for the description of this formation was obtained from Canadian areas, in which a brief reconnaissance was made and in which this formation is best developed. It derives its name from Agawa Lake, where it is well exposed.

Distribution.—The iron-bearing formation occurs only in narrow belts which are not continuous for great distances. The westernmost occurrence is on the portage between Wind and Moose lakes,[a] and the exposures here consist of thin bands of iron oxide, chert, and jasper interbanded. The formation is again found on Sucker Lake, and extends thence northeastward into Birch and Carp lakes. Here it is in character a ferruginous, carbonate-bearing slate. It has been followed into Ontario for about 12 miles in a direction a little north of east through the string of lakes which lie about 1½ miles north of the international boundary on Knife Lake, and are known from west to east as That Mans, Agawa, This Mans, and The Other Mans lakes. In this area it is present in very characteristic development, and consists chiefly of bands of chert, jasper, and iron oxides, with a carbonate-bearing chert and ferruginous slate in very subordinate quantity. The next area in which it is known to occur is on the northeast arm of Ogishke Muncie Lake on both the northwest and southeast shores. Especially on the southeast shore is it well developed. Here it is the carbonate-bearing phase, like that which occurs on Birch and Carp lakes.

In a traverse made southward from Knife Lake along the section line between secs. 29 and 30, T. 65 N., R. 6 W., at about 200 paces south of the lake shore there is a high ridge of Knife Lake slates and graywackes, and the finer-grained slate grades directly down into banded slate and jasper. Only a short distance south of this occurs the basal greenstone on which rests the slate series. Here jasper bands are interlaminated with the bottom part of the slate series which seems to correspond to the iron-bearing formation observed on the Moose Lake–Wind Lake portage, and at the other points noted above. It could not be followed to the east and west. A similar occurrence of jasper bands in the Knife Lake slates has been noted upon Pickle Lake.[b] These occurrences are interesting as showing the existence

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 278.
[b] Grant: Ibid., pp. 440 and 460.

of this iron-bearing formation at a number of places in the area, but in each instance the occurrence is so small that no attempt has been made to show them on the map. Mention of these localities is made under the heading "Interesting localities," page 330.

Exposures.—The exposures are not very numerous, but by means of them the belts may be confidently traced out along the strike, and these are shown on the accompanying map only as far as they have been followed.

STRUCTURE.

The iron formation occurs in narrow belts, having a very uniform strike, but the beds of these belts show varying strike and dip throughout their extent, indicating that the formation has been folded to a greater or less extent. The greatest amount of folding was noticed in that portion of the iron-bearing formation that occurs on the portage between Wind and Moose lakes. At this place the jasper is extremely crenulated and broken. In some places this folding is so extreme that the bands have been fractured and the fragments drawn out into pebble-like areas having no apparent connection with the adjacent pieces; in others, however, the thin string-like ends may be connected with other laminæ of jasper which, when followed out, thicken and grade into other pebble-like areas of jasper.

On the divide on the Wind Lake-Moose Lake portage the iron formation is exposed in three different belts, all three essentially parallel in trend. These are exposed only for a short distance along their strike. The belts have very much the same appearance. They are intensely plicated, and it seems from close study that they all belong to the same horizon; that we have here, in other words, a single iron formation which was intricately folded into the subjacent conglomerates, and that the folds were then truncated, making the formation outcrop at three different places in one horizontal section so as to look like three superimposed belts. It is confidently believed that if the exposures were perfect they could be followed along the strike and connected with one another.

On That Mans, Agawa, This Mans, and The Other Mans lakes, in Canada, the iron formation is closely folded into a syncline, the beds standing practically on edge. Slates occupy the center of the syncline, and in going away from this center in both directions, north and south across the strike of the beds, one goes from lower to lower beds. Moreover, a duplicate succession of the iron formation and other rocks could be determined, showing the structure to be synclinal.

The iron-bearing formation on the Canadian lakes is locally considerably folded, but in no cases does this plication reach the extreme that it does in the Soudan formation. In a way we may consider the plication of the rocks as a measure of the frequency and intensity of the folding. Therefore this very noticeable difference in the folding of the two iron-bearing formations, which are essentially of the same petrographic character, is indicative of the lesser age of the one under consideration, which has been assigned to the Lower Huronian.

The iron formation at the northeast end of Ogishke Muncie Lake is also in a syncline, the formation appearing on both the southeast and northwest shores of the lake The formation is here a carbonate-bearing slate and is especially prominent on the southeast shore, where at several places it occurs in high cliffs with a deep brown ocher-colored crust. When this is removed it discloses a clean, white, almost pure carbonate rock forming the main mass of the ledge. No crumpling could be detected in the formation itself, although the folding of the formation in general is shown by the synclinal structure of the lake basin.

PETROGRAPHIC CHARACTERS.

The iron-bearing Agawa formation consists of two petrographic facies, a carbonate-bearing slaty facies, and a chert, jasper, iron-oxide, and slate facies. These do not occur together, but as they occupy the same relative position, at the base of the Knife Lake slates, they are supposed to belong to the same horizon. The presumption is that the carbonate-bearing facies is of essentially the same kind of material as that from which the chert, jasper, and iron-oxide facies has been derived as the result of processes of metamorphism similar to those which have taken place in the production of the normal jaspers and iron oxides from the ferruginous cherts in the other iron formations of the Lake Superior region (p. 192).

The first phase of the iron-bearing formation, the carbonate-bearing slates, are best developed on the southeastern shore of Ogishke Muncie Lake. There they lie at the base of the Knife Lake slates, resting immediately upon the Ogishke conglomerate, which has been derived from the subjacent Ely greenstone. These carbonate-bearing slates have been traced along the southeast shore of the northeast arm of this lake by means either of distinct outcrops or of marked topographic depressions indicating their continuation. The lake here lies in a syncline in the sediments, and on the opposite shore of the lake—that is, upon the northwest shore—there are carbonate-bearing rocks overlying conglomerates which seem to represent the northwest limb of this syncline and to be a repetition of the carbonates on the southeastern shore. In the rocks on this northwest shore the carbonate-bearing character is not nearly so marked as in those on the southeast limb of the syncline. The high cliffs of the carbonate on the southeastern shore have been noted by previous observers, and have been referred to by Winchell as a limestone. This rock is pure enough at some of the exposures on the southeast shore of Ogishke Muncie Lake to be called a limestone. Microscopic examination shows that it consists chiefly of a carbonate with a small amount of fine-grained cherty silica and some cubes of iron pyrites. The carbonate is decidedly ferruginous, as is shown by the marked yellow, ocherous weathered crust. It passes down into a carbonate-bearing slate and then into the Ogishke conglomerate. In the other direction, upward, it passes into the Knife Lake slates.

This carbonate-bearing horizon is assumed to be the representative of the cherty iron carbonate rocks from which, it is presumed, the iron-bearing rocks at the same horizon at other places were derived.

The second facies of the iron-bearing formation of the Lower Huronian of the Vermilion district is better suited to bear this name than the carbonate-bearing rocks just described, which contain but little iron. This second facies consists of chert, jasper, iron oxide, and slate interbanded. The iron oxide is chiefly magnetite with very little hematite. The chert varies from white to gray and even darker when it has more magnetite mixed with it, becomes red when it contains hematite, and thus passes over into the brilliant-red jasper. This jasper is relatively rare in this iron formation. The slates are the normal gray to bluish and greenish slate carrying more or less ferruginous carbonate, like the above-mentioned cherts. The slates are very much changed, and their clastic characters are not recognizable. They are now very fine-grained, fissile, well-banded slates, consisting of small chlorite flakes, grains of quartz, some ferruginous calcite in rhombohedra, and crystals of magnetite. These rocks show nothing of especial interest, being essentially the same as similar rocks forming the iron-bearing Soudan formation of the Archean and hence are not described here in detail.

ORIGIN.

The normal iron-bearing Agawa formation—that which consists of the chert, jasper, and iron bands, as, for instance, on the Wind Lake-Moose Lake portage, and at the Canadian locality on That Mans, Agawa, This Mans and The Other Mans lakes—is identical, so far as its petrographic character is concerned, with that which has already been described as the Archean Soudan formation. In the course of the description of this formation the conclusion was reached that this had been derived as the result of alteration—the nature of which was also discussed—from an original cherty, iron-bearing carbonate. It is believed that this iron-bearing Agawa formation was derived from the same kind of rock, and as the result of processes analagous to those by which the Soudan formation was produced. In the Soudan formation very little carbonate was found, the reason being, very evidently, that the alteration had proceeded so far that practically all of the carbonate had been changed. Some carbonate-bearing bands were found associated with the jaspers and cherts on That Mans Lake, and they bear a striking resemblance to the carbonates in the Soudan formation. The carbonate-bearing phases of the iron-bearing Agawa formation, to which reference has been made, contain a comparatively high percentage of iron, as is shown by the very rich brown ocherous crust which is found wherever the rocks have been weathered. It is believed that this unaltered carbonate-bearing horizon corresponds to the jasperized horizon, and that these unaltered rocks represent an earlier phase of the jasperized rocks, the alterations by which the jaspers and cherts were produced not having taken place for some reason as yet unexplained.

RELATIONS TO OTHER FORMATIONS.

In the preceding pages statements have already been made of the relations which these rocks bear to the adjacent formations, and the details will be given under the heading "Interesting localities."

At this place the relations of the iron formation to the adjacent formations will be concisely stated. In the first place, it is clear that the iron formation lies above the Ogishke conglomerate, with which it has been found in contact at several places. In every instance it lies above the conglomerate and between it and the overlying Knife Lake slates, into which at other places the conglomerate grades. While this formation is not found everywhere between the conglomerates and slates, in those places where it does occur it always occupies that position. It is clearly, then, an intermediate horizon of comparatively local origin, and our studies have shown that in the Vermilion district it is unimportant from an economic standpoint.

AGE.

In age it is therefore younger than the Ogishke conglomerate, and older than the great mass of Knife Lake slates, and forms a part of the Lower Huronian series.

THICKNESS.

The thickness of the formation varies considerably. On the Wind Lake-Moose Lake portage it has a thickness of about 6 feet. At other places on the United States side of the boundary the exposures are so poor that no correct determinations could be made of its thickness, but at all of these places it appears to be considerably thicker than at the locality just mentioned. The best opportunity for determining its thickness was afforded by the exposures in Canadian territory, where very accurate determination could be made. The best exposures seen in this area are those on the range of hills crossed by the portage from Agawa Lake into This Mans Lake. The rocks are here exposed in a syncline, and on each side of the center of this syncline, which is occupied by a belt of slates, there was found the alternating series of belts of jasper and slates forming the iron-formation complex and having a total thickness of about 50 feet.

INTERESTING LOCALITIES.

The best place at which to study the characters of the Agawa formation is on the string of lakes known as That Mans, Agawa, This Mans, and The Other Mans lakes, which lies at an average distance of about 1½ miles north of the international boundary on Knife Lake, and trends about N. 45° E. Exposures of the formation may be seen at intervals along the south shore of the string of lakes, on the islands near the center, and on the necks of land which separate the lakes and across which the portages run. On the point north of the north end of the portage that comes from Emerald Lake on the south to That Mans Lake there is a series of interbedded jaspers, cherts, iron ore, carbonate-bearing slates, and normal slates and graywackes, having a width of about 50 feet. The dips on this exposure are all to the south. No dips were taken which were less than 55°, and most commonly they were 60°. On the southeast side of the bay northeast of this point there is an excellent exposure which gives a cross section of the iron formation. The best exposures in this area, however, are those on the range of hills crossed by the portage from Agawa Lake into This Mans Lake. On the hill immediately north of the west end of the portage there is well exposed a series of narrow interlaminated bands of jasper, iron oxide, chiefly magnetite and chert, with some slaty bands. Between these, and interlaminated with them, there occurs well-banded and thinly laminated gray slate. These interbanded belts of slates and iron formation proper continue to outcrop along the hill to the east. From this hill a north-south traverse was made, and here it was found that the youngest rock, that which occupies the center of the area, is a gray sericitic slate having a width of about 75 feet, and striking about N. 45° E. On each side of this—that is, both north and south of it—there occurs the iron formation, consisting of a complex of three belts of the iron formation proper, and two intervening belts of slate. The approximate width of the complex on each side of the central belt of slates is 50 feet. North and south of the iron formation there is a considerable width of gray slates, which are in their turn succeeded by interbedded graywackes and slates, and, finally, north and south of these sediments comes the Ely greenstone as basement. This greenstone was not seen at just this locality, but its relation to the sediments was obtained on the strike of these beds to the west, and but a short distance away from this point. From the repetition of these various rocks it is clear that the structure at this place is synclinal. The greenstones on the south and north represent the oldest rocks, the younger sediments occurring above them toward the center of the syncline. The structure of the rocks evidently determined the topography in this region. The lakes lie in the center of and at the bottom of this slate syncline. It is true that at this place the iron formation does not lie absolutely at the base of the slates, since there are some slates between it and the conglomerate. Nevertheless it occurs essentially at the base of the formation. This was an area in which, as is shown by the rocks, the conditions of deposition were rapidly changing. Slates were at first formed, and as the conditions changed they graded into the rocks forming the iron formation, which in their turn, as the conditions again changed, graded again upward into normal slates. This was repeated at least three times. On good exposures the belts of iron formation proper are made up predominantly of jasper, iron oxide, and chert, but here and there slate bands are present, and on the sides of such a belt the slate gradually increases in quantity, jasper and ore gradually diminishing, until we pass into a belt of finely laminated slate showing on the weathered surfaces alternating pink, white, and greenish bands, with which there is practically no jasper.

The carbonate-bearing rocks occur at various places on Birch Lake. They were always found along the contact between the greenstones and the slates, and were a sure guide to the close proximity of the greenstones. No jasper was found with these rocks. Essentially the same conditions prevail on the north side of Carp Lake. At a number of places here the belt of ferruginous carbonate-bearing slate was found between the greenstones and the slates. At one place a series of bands of chert and jasper was observed. These occur at the west end of the north arm of Carp Lake, on the little point just opposite an exposure of the Ely greenstone. They appear very similar to the slates and jasper that occur in the series at This Mans Lake, northeast of this place. The greenstone shows its typical ellipsoidal characters and is separated from the jasper by an interval of 2 feet. This occurrence corresponds very closely to that on the north flank of the small greenstone anticline south of Knife Lake, in secs. 29 and 30, T. 65 N., R. 6 W.

One can readily see how, in the course of the deposition of slates of such great thicknesses as those that make up the Knife Lake slates of the Lower Huronian in the Vermilion district, there could occur at different times conditions favorable for the deposition of rocks from which might be derived materials similar to the iron-bearing formation. We would thus expect to find here and there throughout these slates rocks essentially similar to those of the iron-bearing formation. In this way we may account for the occurrence in the slates west of Ely, near the east quarter post of sec. 4, T. 62 N., R. 13 W., of a series of alternating chert and cherty-slate layers bearing some iron. The less cherty layers contain a considerable quantity of iron, and weather with fairly brilliant red color. In this way, by the alternation of the red bands and the gray chert bands, these rocks simulate the jaspers and cherts of the iron formation proper. A somewhat similar occurrence is that noted at the south end of the portage coming into the north side of Pickle Lake, where there are alternating slate and purplish chert bands, striking N. 35° E. in the midst of the Knife Lake slates. These are probably the continuation of similar chert bands which occur upon the southeast shore of Pickle Lake.

On the bare hills crossed by the Wind Lake-Moose Lake portage tnere are good exposures of the iron-bearing Agawa formation, showing its relationship to the adjacent rocks. To the north is a conglomerate consisting of greenstone pebbles with occasional pebbles of acid rocks, feldspathic porphyry, rhyolite-porphyry, and granite. Above the conglomerate is about 3 feet of coarse graywacke and fairly coarse slate, followed by a belt about a foot and a half in thickness, in which the interbanding is closer with the slate predominating. Then comes 3 feet of the iron-formation member, consisting chiefly of the black chert—black jasper as it is sometimes called—greenish chert, and some red jasper, although this is in rather subordinate quantity. With these cherts there are found a few fine-grained slaty layers ranging in thickness from a fraction of an inch to 4 inches. This band of the iron-bearing formation is 6 feet wide. South of this iron-bearing formation, and making up the remainder of the section of this hill, and exposed for a hundred feet or more, across the strike, is a conglomerate similar to the conglomerate below the jasper band in its essential characters, but different from it in several important respects: First, it contains several narrow but minutely crenulated complex layers of interlaminated graywacke, slate and jasper; second, it contains many roundish, lenticular, and also angular areas of black chert, red jasper, and a black slaty-looking jasper, and various combinations of these. When these areas are examined closely, they appear to be true beds which have been broken by dynamic action. The undoubted jasper formation itself is extremely crenulated and broken. Generally the pebble-like areas continue out into thin strings which may be connected with laminæ of jasper, but this is not invariably the case. If the jasper is in true fragments the slate and graywacke also are in true fragments, for they, too, occur in this material in similar roundish or angular masses. It has been suggested that this conglomerate lying above the jasper belt first described is younger than the jasper, and that these irregular masses which have just been mentioned are pebbles derived from it and lying in the conglomerate. While one can understand how this interpretation could be made, the conglomerate above the jasper band being regarded as evidence of another structural break, nevertheless the undoubted bands of jasper in the conglomerate, and the certainty that many of these irregular areas are derived from these bands and owe their character to dynamic agencies, are strong evidence against this view. It may be suggested that it is very probable that some of these irregular masses may be due to a later infiltration of jasper material.

The interbanding of the jasper, slate, and conglomerate is particularly well seen about 50 paces west of the trail near the top of the hill. Here in a width of 6 feet one may count 6 distinct bands of jasper interbedded with fine graywacke and slate. The bands which were counted as jasper bands contain thin laminæ of slate ranging from a fraction of an inch to an inch across, and, vice versa, the bands counted as clastic sediments contain minute bands of jasper. At this place the extreme mashing to which the rocks have been subjected in this area is beautifully illustrated. The jasper is plicated in an extremely complex manner. In some places it bends without major fractures, and in others it has broken through and through. In places narrow bands of the jasper are severed by diagonal shearing planes into areas which are now more or less lenticular in shape, and may be immediately in juxtaposition or somewhat removed from one another. In the clastic sediments lying between the continuous jasper bands there are some angular and roundish areas of jasper, but these appear to have been derived by dynamic action from the continuous belts of jasper, and not to be clastic fragments deposited by water in their present place. The whole is made more complex by secondary veining and jasperization of the rocks since the folding of them took place. South of the last-mentioned jasper belt, there occurs, measured across the strike, about 50 feet of graywacke, slate, and conglomerate. On the south side of the exposure this material changes into a fine-grained conglomerate which in the space of 3 or 4 feet grades up into a slate which underlies the 150 to 200 paces intervening between the last jasper exposure on the ridge and Moose Lake. A close examination of these jasper bands on the hills shows that the second one to the south, which lies between two ridges of conglomerate, is of just about the same width as the jasper band which appears farthest north. This suggests that the double appearance of this band is due to infolding, the closeness of which is evidenced by the extremely plicated character of the iron formation itself. East of this ridge, in the low ground, the iron formation was found exposed, but so poorly that it was impossible to determine its width. It is followed to the south by slates, whereas the conglomerates are the nearest rocks exposed to it on the north. It seems almost unquestionable that we have here an iron-bearing formation of very limited thickness, which occupies a horizon between the conglomerates north of and below it, and the younger slates south of and above it. This iron formation could not be traced to the east or the west of the area mentioned. At one place, however, on the bare hill in the SE. ¼ of sec. 16, T. 64 N., R. 9 W., overlooking the swamp which runs down to the southwest end of Newfound Lake, occur good exposures of a very feldspathic fragmental rock. This coarse fragmental is interbanded with fine-grained slates. Here were found, in a few places, interlaminated with the slates, narrow bands of black chert up to 3 inches in width. This chert is conformable with the slates, and seems to be contemporaneous with them, but may possibly consist of silicified lenses of carbonate-bearing rock. These bands disappear after being followed for only very short distances. They occur fairly close to the greenstone to the northwest, on which rest these sediments in unconformable relations without intervening thick masses of conglomerate.

KNIFE LAKE SLATES.

One of the largest lakes on the canoe route along the international boundary has been known since the time of the fur traders as Knife Lake (Lac des Couteaux). The lake was so named because of the flinty conchoidally fracturing slates which surround it and which, with their sharp knife-like edges, cause a great deal of inconvenience to the moccasined traveler, and even to him with thick boots. Probably this name is but a translation of one given to it by the Indians long before the advent of the French voyageurs. At any rate, the name aptly describes one of the characteristics of the slates, and the lake bearing the name is so prominent a feature of the hydrography of the district that the name has been given also to the slates.

PETROGRAPHIC CHARACTERS.

Macroscopic characters—In mapping the Knife Lake slates it has been found desirable to include with them numbers of beds of grit and fine-grained conglomerates which belong structurally with them. These, however, are so unimportant relative to the great mass of the slates that they will not be considered in the further description unless they possess especial characters that warrant reference to them. The slates vary from those which are exceedingly fine grained and aphanitic to grits. As a rule, the exceedingly fine-grained forms predominate. They are for the most part not earthy clay slates, but are flinty, break with a ringing sound, have conchoidal fracture, and form fragments with sharp, cutting edges. The normal clay slates are in decidedly smaller quantity than the above-mentioned flinty forms. The color of the slates is in general rather dark on fresh fracture, varying from dark gray and olive green to bluish black. Associated with these dark slates are light-grayish and greenish-colored slates and graywackes. Occasional bands of white to gray and purplish black cherts occur with the slates. On weathered surfaces the normal slates have a light gray to light-brownish color. The flinty slates, however, weather with an almost snow-white crust, showing macroscopically by this weathering that they consist to a very considerable extent of silica in an exceedingly fine state of division. This is in strong contrast to their invariable dark bluish-black color on fresh fracture.

In general, there is a difference in the slates in different portions of the district, due primarily to the character of the rocks from which they are derived. As a rule, where the Knife Lake slates and graywackes lie next to the Archean greenstones, without large masses of Ogishke conglomerate between them, they are green, and grade into the normal gray and blue Knife Lake slates, made up in large proportion of granitic débris only at considerable distance from the greenstones. Slates of this greenish color are especially noticeable on Birch, Carp, and Ensign lakes, and in the area southwest of Emerald Lake. From Moose Lake east to Ensign Lake the slates range from the greenish ones, looking much like extremely fissile green schists, to sericitic, gray, fissile slates, which predominate. Northeast of Ensign Lake the slates again grade into the green ones, and in Bass Lake the normal Knife Lake slates are at some places very flinty, and at others have white weathered surfaces. There occur with the slates at times graywackes which are rather puzzling. They are more intimately associated with the slates than with the conglomerates, and hence will be described in this place. South of the east end of Moose Lake, and in fact at a number of places on the hills south of this lake, especially in the vicinity of the portage from Moose Lake to Flask Lake, there occurs a graywacke which has a greenish color, and from its green background there stand out very prominent rounded porphyritic feldspars. The appearance is very similar to that of a feldspathic porphyry which occurs in the immediate vicinity of these graywackes. Discrimination between the two is difficult. In fact, there is evidently a gradation between them, the graywacke representing the disintegrated portion of the porphyry, the particles of which have been but slightly moved and worn. Bedding is not very distinct in it. It is now very schistose, and one can trace the passage from this schistose graywacke into the fairly massive porphyry.

Somewhat similar feldspathic sediments with the feldspars appearing almost like phenocrysts occur on the bare hill in the SE. $\frac{1}{4}$ of sec. 16, T. 64 N., R. 9 W., just west of the southwest end of Newfound Lake. These occurrences correspond very closely to those graywackes which occur at Vermilion Lake (p. 288) in immediate contact with the various acid intrusives, and which in many cases can not be distinguished from them in the field.

Microscopic characters.—The microscopic examination reveals nothing of especial interest. The essential primary constituents are feldspar, quartz, brown mica, white to green and violet-brown pyroxene, and greenish-brown hornblende, and then there is always an amount of the fine interstitial material, the very fine product of the attrition of the grains of minerals and fragments of rock forming the slates and graywackes. This material in all cases studied has been recrystallized, and does not show up now as a dark interstitial mass except by low power. By high power the individual constituents can usually be recognized and will be referred to below. In the graywackes which are associated with the slates there occur occasional minute fragments of the various rocks which have been mentioned in previous pages as forming a part of the conglomerates. The primary mineral grains and likewise the interstitial dust have very frequently been extensively altered, and from these have been produced the following secondary minerals, which in some cases, where the rocks are completely recrystallized, are the sole constituents: Chlorite, epidote, sericite, actinolite, massive dark-brown and green hornblende, quartz, calcite, and pyrite. The material between the grains in the coarser sediments is made up of sericite, chlorite, epidote, quartz, and feldspar, and this is believed to have been produced, as stated above, from the fine detrital material originally lying between these grains. In the very fine-grained rocks, where the crystalline character of this interstitial material is recognizable, but where the individuals of it could not be determined, they are presumed to be the same as those just enumerated. These materials are present in varying proportion, which produces, of course, the differences in color and chemical composition of the rocks; for instance, some of the lighter colored rocks—the light cherts, for example—are composed essentially of quartz in very fine crystalline particles. Other rocks are made up essentially of quartz and feldspar in waterworn grains, with some of the fine interstitial material between. Others again contain, in addition to the quartz and feldspar, a large quantity of pyroxene and of hornblende, and are very dark, usually dark green, and apparently fairly basic in character. A few rocks contain calcite in considerable amount, but never in sufficient amount to be called limestone. Moreover, this calcite is believed to be of secondary origin, derived from the alteration of the minerals forming the rocks or else introduced from other sources by infiltration.

The general alteration which the minerals of these rocks have already undergone has been referred to. The addition of new minerals is clearly shown in the case of the hornblende of some specimens. In these we find the fragments of dark-brownish hornblende surrounded by recently added massive light-greenish hornblende. The hornblende grains in some cases have been increased to two and even three times their original length.[a]

The changes which have taken place in some of the rocks show very well how, by somewhat further changes, banded crystalline schists might be produced which would offer no clue but the banding to a determination of the kinds of rocks from which they were derived. Thus some of the fine-grained sediments, rich in hornblende, have nearly all of the pieces of hornblende, very commonly cleavage pieces, arranged with their long

[a] Enlargements of hornblende fragments, by C. R. Van Hise: Am. Jour. Sci., 3d series, Vol. XXX, 1885, pp. 231-235.

directions parallel. Many of these have been added to by secondary growths of massive hornblende or of fibrous actinolite. This addition of the secondary material only tends to emphasize the parallel arrangement of the particles, since the greatest addition has been made on the ends of the fragments. This was noticed in some of the graywackes made up almost exclusively of feldspar and hornblende, with mica next in abundance, and very little quartz. In such rocks the biotite alters to chlorite. Alteration of the feldspar with the production of new minerals also takes place, and a few quartz grains alone remain to give evidence of the clastic character of the constituents. When such rocks take part in orogenic movements the quartz may be crushed, and in general a better degree of schistosity produced than previously existed, and as a result of such movements hornblende-schists may eventually be produced. The banding of these hornblendic sediments has been referred to. These bands of finer and coarser materials have essentially the same composition. There also appears to be a relation between the fineness of the hornblende grains of the original sediments and the character of the new amphibole. Thus it was noticed that in the alteration of the very fine-grained sediments the new amphibole is added in the form of fine actinolite needles, whereas in the coarser graywackes the new amphibole is in general a massive hornblende. The final product of the metamorphism of these rocks would probably retain this essential difference, so that we would get fine- and coarse-grained amphibole-schists, or possibly banded actinolite and hornblende-schists.

There is also a banding due to the separation of the kinds of minerals. Thus there will be some dark bands made up essentially of hornblende and mica with but little feldspar, and alternating with these bands there will be bands of feldspar with but little hornblende or biotite. When such rocks are metamorphosed there will be no very great migration of material from the one band to the other, and certainly the original differences in the bands will be shown to a certain extent in the differences in the bands in the metamorphic product. Presumably the final product would be an amphibole-schist complex made up of alternating bands of amphibole-schists rich and poor in feldspar or other secondary products—quartz and feldspar, perhaps—derived from the original feldspar and of different color, corresponding to the difference in mineral composition.

METAMORPHISM OF THE KNIFE LAKE SLATES.

The rocks possessing the characters briefly described above are those which we may call the normal Knife Lake slates. Even these so-called normal slates have been very much metamorphosed. The metamorphism has been caused by the infiltration of material (chiefly silica and calcium carbonate), by the cementation of the particles by these substances, and by the further cementation of the rock by chemical changes of the fragments, which produced new minerals and also caused the secondary enlargement of the old mineral fragments. These rocks show locally the effect of orogenic movements in more or less well-developed schistose structure and fracturing.

At several places in the district the slates are in contact with later igneous rocks, both acid and basic, and have been metamorphosed by the intrusion of these rocks. In all cases the rocks, as stated above, have been affected by processes of cementation and to a certain extent by orographic movements, and in some instances these sediments have been metamorphosed by acid intrusives and then have been acted upon by the great Keweenawan gabbro and still further changed. Hence it is exceedingly difficult to discriminate between the kinds of metamorphic products which are due to each one of these agencies. In the following paragraphs a brief description will be given of the macroscopic characters of those Knife Lake slates which have been metamorphosed by the contact action of the acid and basic intrusives, and which occur in the four most important areas: (1) South of Tower, along the Duluth and Iron Range Railroad, near milepost 92; (2) on the Kawishiwi River; (3) at Snowbank and Cacaquabic lakes; and (4) in the vicinity of Gobbemichigamma and Paul lakes.

Contact effect of the granite.—The sediments metamorphosed by the Giants Range granite are well exposed near milepost 92 on the Duluth and Iron Range Railroad, south of Tower, and this place is readily accessible. They are also well exposed on the Kawishiwi River, near the mouth of that river where it empties into Farm Lake; along the shore east thereof; and on the portage leaving the bay of the river, in the SE. $\frac{1}{4}$ of sec. 30, T. 63 N., R. 10 W., leading southeast to Clearwater Lake. In places some conglomerates occur, especially on the islands in the river in sec. 26, T. 63 N., R. 11 W., but the coarse sediments are very subordinate. The sediments are now metamorphosed to mica- and amphibole-schists. Occasionally garnets have been produced as the result of contact action. The metamorphosed rocks retain the sharp banding of the original sediments, and there is also noticeable at many places a rapid alternation of bands of different grain and composition. These bands are composed of feldspar and quartz, with epidote, amphibole, and mica. Variation in the quantity and combination of these minerals causes a difference in their appearance. A study of almost any of the exposures in the area south of the Kawishiwi River in which these rocks occur as outlined on the maps shows clearly the cause of the alteration. They are penetrated at numerous places by dikes of granite which are offshoots from the great mass of Giants Range granite which lies in contact with these schists on the south. The granite dikes become more numerous as we go farther south nearing this contact, and at the south end of the portage above referred to, on the ridge just overlooking Clearwater Lake, the granite dikes are more numerous and of larger size than at other places. Here, moreover, there is an exceedingly good example of an eruptive breccia. The breccia consists of dark-gray and black schist fragments derived from these metamorphosed sediments, which are cemented by a matrix of the grayish and pink Giants Range granite. Farther south, within the main mass of the granite, as on the islands in Clearwater Lake and elsewhere, it attains its normal grain and characters. In the dikes its characters are likely to vary as well as its grain, depending upon the size of the dikes and the position in the dikes from which the specimen is taken. Mountain-making movements may have affected and unquestionably did affect these sediments to some extent. It probably aided in making them schistose. What other effects it may have had have been concealed, however, by the contact effects of the intrusive granite.

In the vicinity of Snowbank Lake, especially on the bare hills southwest of it, in secs. 10 and 17, T. 63 N., R. 9 W., the Knife Lake slates are well developed and are splendidly exposed over large areas. The slates have been intruded by the Snowbank granite and from them have been produced mica-schists, which predominate, with subordinate amphibole-schists. The same kind of effect has been produced by the intrusion of the Cacaquabic granite on the slates nearest it, although, since the slates are not exposed very near the granite, the effect is not so marked.

The microscopic study of these contact rocks of the granite shows nothing of especial interest. The rocks are, as said, mica- (biotite-) and amphibole-schists. The minerals constituting them are biotite and some muscovite, hornblende, actinolite, quartz, feldspar, epidote, and garnet occasionally.

Contact effect of the gabbro.—The effect of the intrusion of the Snowbank and Cacaquabic granites on the surrounding sediments has been, as said, to produce mica-schists, and, in a subordinate degree, amphibole-schists. Subsequent to this intrusion these schists must have been affected by orographic movements, but the effect of these movements is not recognizable, for at a still later date the great Keweenawan gabbro was intruded into the rocks of this district and produced important contact effects upon them. It is practically impossible now to discriminate between the products of these different periods of metamorphism. In general the sediments in the vicinity of the granites and gabbro have been transformed into mica-schists and amphibole-schists, whose chief characters may have been produced by the intrusion of the Snowbank and Cacaquabic granites alone. South and southwest of the Snowbank granite, however, in the vicinity of the gabbro, fine-grained rocks are very commonly spotted and resemble the so-called spilosite, the spotted contact rocks of the diabase. This peculiar phase of the metamorphism is probably due to the contact action of the gabbro. Some of these spotted rocks are at present about three-fourths of a mile away from the nearest exposures of the gabbro. It is, however, not necessary to believe that the gabbro was able to affect the sediments at this distance. It seems almost certain that at one time the gabbro extended farther north than the line where its present northern boundary appears, and that at that time it overlay these rocks, so that in reality it was separated vertically from the rock at the level of the present exposures by perhaps only a few hundred feet of intervening rock at most. Similar spotted rocks occur in the slates upon the prominent hill north of the west end of Paul Lake, in sec. 32, T. 65 N., R. 5 W. The total absence, near these spotted sediments in this area, of any acid intrusives which could have produced them, and their presence here in close proximity to the gabbro, seems to show pretty conclusively that the spotted rocks in this place, as well as the similar ones mentioned above as occurring south and southwest of the Snowbank granite, are due to the gabbro contact action, and not to that of the granite.

Some of the best places at which to study the slates that have been extremely metamorphosed are on the east, southeast, and south shores of Gobbemichigamma Lake. Here the metamorphism of the slates by the gabbro has not been complicated by a previous metamorphism of the slates by a granite, as is the case in the vicinity of Snowbank Lake. At various places here the sediments are exposed, showing in places their characteristic banding, but they have been so extremely altered that but for this banding their derivation from the slates might not be recognized. The sediments have acquired for the most part a granular character and brownish color, and weather rather readily. As the result of their peculiar saccharoidal appearance the name "muscovado," having reference to their resemblance to brown sugar, was given to them by Alexander Winchell.[a] Their true character was not recognized by him. Since it is clear that they are but metamorphosed phases of the sediments, it seems totally unnecessary to continue the use of this term, which can not be applied to a rock of definite composition, especially since, as pointed out by H. V. Winchell[b] and U. S. Grant,[c] two different kinds of rocks, metamorphosed sediments, and certain phases of the gabbros, are included under this term merely because they bear a superficial resemblance to one another. This metamorphism has been produced by the Duluth gabbro, which at a number of places has been found in direct contact with these rocks. One of the best places at which to study the relationship is on the small island crossed by the town line on the southeast side of Gobbemichigamma Lake, and also on the point north of the portage from this lake east into Peter Lake. At these places the sediments are overlain by the gabbro, and the contact line between them can be traced very clearly. The vertical thickness of the contact rock as measured on Gobbemichigamma Lake seems not to have exceeded 50 feet. At many places along the shore there is a horizontal exposure of much more than this in width. This represents, however, the beveled edge of the contact zone, and since no data for the reconstruction of the removed material showing the inclination of the surface overlain by the gabbro can be obtained, no measurement can be made of the true width of the contact zone.

On the island referred to above, and immediately next to the gabbro,

---

[a] Geol. and Nat. Hist. Survey of Minnesota, Fifteenth Ann. Rept., 1886, pp. 183 and 351.
[b] Ibid., Seventeenth Ann. Rept., 1888, p. 130.
[c] Ibid., Final Rept., Vol. IV, 1899, p. 478.

the sediments are, as above stated, granular and in character resemble much more closely the gabbro than they do the sediments proper. At some distance away from the gabbro contact rounded masses of dense greenish and gray rock begin to appear, surrounded by the granular contact product. This gives a conglomeratic appearance to the exposure. A little farther away from the gabbro, on a vertical exposure at the lake shore, these pebble-like areas were seen to be aligned, and eventually to pass into parallel unbroken bands. The explanation of this occurrence is that the gabbro in contact with the sediments caused them to be altered to the peculiar granular contact product. The alteration naturally was most effective nearest the gabbro, and gradually spread, following along the cracks in the rocks, the vertical as well as the horizontal cracks. Near the gabbro all of the sediments were changed. Farther away the blocks or fragments of sediments were changed on the exterior most completely. Sometimes this change was so far reaching as to convert into the granular contact product most of the sedimentary block, and to leave only a small core of the block, but even this was very much modified. Such a core looks like a pebble in a matrix, and gives the rock a conglomeratic appearance. Still farther away the alteration was less, following only along certain of the most prominent parting planes, and leaving the sediments in bands.

PETROGRAPHIC CHARACTERS OF THE METAMORPHOSED SLATES.

Microscopic characters.—It would require a very much more detailed study of these metamorphosed slates than has yet been made to enable one to describe fully the various changes through which the original sediments have passed in becoming the various kinds of rocks above described, and numerous chemical analyses would be required in order to determine just what, if any, changes in chemical composition had been produced by the contact action of the gabbro.

The chief constituents of these contact rocks are: Plagioclase feldspar, little quartz, biotite, muscovite, chlorite, green, bluish, and brownish hornblende, light-green pyroxene, hypersthene, olivine (?), titanite, epidote, garnet, and magnetite. The mica-, hornblende-, and pyroxene-schists and gneisses derived from the slates by the contact action of the gabbro almost invariably contain very little quartz, but are full of a rich-brown mica and hornblende, with feldspar present in large quantity. The dark constituents predominate, and the mica is usually more abundant than the hornblende. With these constituents there occur varying amounts of hypersthene, light-green pyroxene, olivine (?), and magnetite. In some of these gabbro contact rocks the hypersthene exceptionally is the predominant constituent, usually associated with considerable mica and magnetite. In general we may say that the production of minerals rich in magnesium and iron, in particular hypersthene, brown mica, and magnetite, is characteristic of the gabbro contact. These are, of course, the kinds of minerals which, a priori, would be expected in rocks greatly affected by a gabbro magma. Analyses of these rocks and of the rocks from which they were derived have not been obtained, and indeed a great many would be required to prove the thesis that an actual transfer of material from the gabbro to the surrounding sediments had taken place. However, in view of the production in such large quantity of the magnesian and iron minerals in these sediments it is believed that such a transfer of some magnesia and iron has actually taken place from the gabbro magma to the sediments now containing these minerals. The fact that these minerals occur more abundantly in the rocks near the gabbro than in those farther away supports this view.

The spotted contact rocks, the spilosites, are known to occur as the result of the contact action of diabases and gabbros, and those occurring in this district are believed to be without doubt the product of the gabbro contact and to be characteristic of it. The spilosites from the Vermilion district are fairly common in the area southwest of Snowbank Lake. They are very similar to the spilosite described from the Crystal Falls district of Michigan,[a] and, like them, the spots, which are in general of oval outline, occur isolated or united along the long axis of the ovals in a series. These spots are composed of aggregates of muscovite, epidote, little chlorite, and sphene, in a fine groundmass (which predominates) of muscovite, chlorite, epidote, sphene, feldspar, and quartz.

Somewhat different are the spotted rocks occurring north of Paul Lake, for example. The white material forming the spots has essentially the same single and double refraction as feldspar. The material includes biotite and

---

[a] Mon. U. S. Geol. Survey Vol. XXXVI, 1899, pp. 206–207. Also a contribution to the study of contact metamorphism, by J. Morgan Clements: Am. Jour. Sci., 4th series, Vol. VII, 1899, pp. 81–91.

chlorite flakes, and particles of iron ore. Grant[a] has described cordierite occurring in similar rocks on Gobbemichigamma Lake, to the southwest of the area above referred to. Very possibly the material forming these white spots is cordierite, but no conclusive proofs of this were obtained.

THICKNESS.

It has already been stated that in portions of the Vermilion district the Knife Lake slates show a very great width. From this fact alone one not taking into consideration the intensely plicated condition of these rocks and hence the possibility, or even the certainty, of more or less repetition, might be led to infer that these slates are of enormous thickness.

This folding, of course, points to a probable reduplication of the beds. While the slate area can by no means be described as homogeneous, nevertheless it is true that clearly recognizable key rocks are wanting. Consequently there must be numbers of anticlines and synclines which it has not been possible under the existing conditions to recognize. These facts render it exceedingly difficult to make any authoritative statement as to the thickness of this series. At one place, however, the structure is fairly simple. Between Ogishke Muncie Lake and Gobbemichigamma Lake, two of the large lakes in the eastern part of the district, there are two small lakes, Fox and Agamok lakes, which occupy the low ground. North of these there is a high ridge occupied by Archean greenstone with the Ogishke conglomerate on its southern flank. South of this string of lakes there is a second ridge of Archean greenstone, forming a very marked topographic feature. Between these two ridges we find the Knife Lake slates, showing a number of good exposures. Traverses across this area from north to south gave at first a series of south dips, gradually becoming flatter and flatter, until the bottom of the syncline just south of the lakes mentioned as lying in the bottom of the depression was reached, where the flattest dips were found. Continuing across as we ascend the south ridge, this succession of dips is repeated in reverse order—i. e., the steepest dips are nearest the ridge, and the dips are to the north. Moreover, it was possible to observe a repetition of the rocks. The slates here evidently occupied a distinct syncline, and moreover this syncline seems to be a simple one.

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, pp. 657–658.

From the data obtained here the total thickness of the slates across this syncline is calculated to be 5,000 feet, which divided in half gives us a maximum thickness here of 2,500 feet. It is impossible to state positively whether or not this represents the maximum thickness of the slates for this area. The presumption is, however, that the maximum thickness here obtained does not represent the maximum original thickness of the slates, as they must have originally occupied the entire basin between the older rocks, and possibly had a much greater vertical extent, the rocks above those now remaining having been of course long since removed by erosion.

INTERESTING LOCALITIES.

Structure and relations of the slates.—On Carp and Birch lakes the relations of the topography to the geologic structure are well indicated. The central headland of Carp Lake, as well as much of the western bay and the headlands beside the narrows, are composed largely of a coarse graywacke which is characteristic of the lower part of the slate formation. These headlands are directly along the strike of the plunging anticline at the east end of the lake. Corresponding to them there is an eastward-projecting headland in the west bay of the lake, and this also is composed of the coarse graywacke. The southern part of the western bay is composed of the normal slates. Thus, while Carp Lake is as a whole a part of a monocline dipping to the south, it very plainly has a subordinate anticline through the center which makes the graywacke at the base of the slates the predominant rock exposed.

Birch Lake, west of Carp Lake, was found to be surrounded by slates for about a mile at its eastern end. Then, at a little bay occurring just east of the long westward-projecting point, greenstone comes out upon the north shore for a short distance. The slates appear again upon the point to the southwest of the greenstone. The greenstone is again exposed in the next bay to the north, and with a minor fold swings up into the extreme north bay and thence inland, the shore being composed of slate. The relations are such as to indicate a series of infolds, the slates occupying the depressions, appearing as reentrants on the lakes, and the greenstones occupying the headlands and highlands to the north.

Topographic depressions usually separate the Archean greenstones from the slates which lie near them, hence the sequence of rocks from the greenstones to the slates is usually interrupted. A number of contacts have been found, however, and in every instance where careful examination was made at least a narrow belt of conglomerate derived from the greenstone intervened between the greenstone and the slates. The localities at which such conglomerates occur are described under the heading "Ogishke conglomerate" (p. 317 et seq.). These conglomerates were found to be present in practically every case in which careful search was made, and this fact is the warrant for indicating on the maps in many places continuous belts of conglomerate between the Knife Lake slates and the Ely greenstones. This insertion has been made especially for the reason that thereby the structure of the district can be made plainer. In almost every case, however, in order to show this belt, it has been necessary to magnify many-fold the true thickness of the conglomerate. In the NW. ¼ of sec. 17, T. 63 N., R. 9 W., contacts between the Knife Lake slates and the ellipsoidal Ely greenstone can be found at many places. Here there is an eastward-plunging trough of sediments infolded in the greenstones. Here and there a narrow band of conglomerate occurs between the slates and the greenstone; elsewhere, however, actual contacts have been found in which the slate lies next to a zone of very schistose greenstone, which then grades down into the normal greenstone. Evidently these deposits were formed in a fairly protected area, as is indicated by the predominance of the slates over the coarser graywackes and the scarcity of conglomerates along the border of the greenstone.

About 120 paces south of the Moose Lake end of the Moose Lake-Flask Lake portage there occur numerous small outcrops of a porphyritic greenstone which has a more or less schistose green matrix, with numerous white porphyritic crystals of feldspar evenly distributed through it. Toward Moose Lake this porphyry becomes more and more fissile until finally it passes into a schist. This schist is so beautifully and finely laminated and fissile that it can almost be spoken of as a slate. Upon the surfaces the flattened phenocrysts are shown. This schist belongs with the Knife Lake slates. South of it lies a graywacke made up of disintegrated material derived from the porphyry, with which it lies directly in contact. There are no pebbles in this material which can be clearly recognized as such. If any exist they merge into the matrix, and the two rocks, the schistose porphyry and the grit derived from it, resemble each other so strongly that it is only after very close study that they can be discriminated.

At the southwest end of the lake, whose tip just extends into the NE. $\frac{1}{4}$ of sec. 11, T. 64 N., R. 8 W., there is a dike of granite-porphyry which cuts across the bedding. Other granite dikes must occur throughout this district cutting these slates, although few of them have been found. One, for instance, occurs upon the south side of the large island in Knife Lake north of sec. 31, T. 65 N., R. 8 W.

Contact metamorphism of the slates.—An excellent place at which to see the character of the metamorphosed Knife Lake slates is along the Duluth and Iron Range Railroad, near milepost 92. This place is also very easily reached.

In going south from Tower after passing the south side of the Ely greenstone one observes the following series of sediments:

On the first exposure south of the greenstone we get slates and graywackes, which are, even in this first exposure, somewhat metamorphosed—that is, they are very firm slates and quite thoroughly indurated graywackes, but still show very clearly their unmistakable sedimentary characters. The first granite dikes observed in these sediments occur about a mile south of their most northern outcrop. Continuing south from the first outcrops of the sediments on the railroad, the ones to which we come thereafter take on a more and more altered character as we go farther south. At milepost 92 the presence of good conglomerates with accompanying finer sediments showing well-marked sedimentary structures such as normal and current bedding, indicates with absolute clearness the mode of origin of the rocks. The microscopic study of these rocks is not so satisfactory as the macroscopic; the changes which the rocks have undergone have obliterated all features which would enable one to determine with absolute accuracy by means of the microscope the original characters of these rocks, although the coarse macroscopic structures still remain. Farther south the outcrops become scarcer as we approach the great muskeg area in the low ground north of the Giants range. Nevertheless here the few outcrops which were observed are exceedingly indurated banded rocks which can be more properly spoken of as mica-schists than as graywackes. Still farther south the rocks are mica-schists and mica-gneisses, with very much contorted banding, and are cut by granite dikes. The change in the character of the rocks as shown on the outcrops seems to point conclusively to the fact that these changes are due to an increasing metamorphism of these sediments, corresponding to our approach to the main Giants Range granite mass lying far to the south. In this western portion of the area the center of intrusion lies in the Giants range, a number of miles south of the area described in this monograph.

The metamorphism of these Knife Lake slates can be seen to advantage in the vicinity of Snowbank Lake. On the north shore of Snowbank Lake, at a number of places, mica-schists may be found which are cut through and through by dikes derived from the Snowbank granite. These schists, when followed inland for a considerable distance, are found to grade into the less and less altered sediments, until eventually the normal Knife Lake sediments are reached. Somewhat similar metamorphosed mica-schists can be observed upon the portage between Round Lake and Disappointment Lake. These have been metamorphosed by the gabbro which lies only a short distance to the south, although in all probability they were first affected by the intrusion of the Snowbank granite. Here the cleavage is parallel to the bedding. This mica-schist resembles in a remarkable degree the mica-schist[a] which occurs as the upper part of the Upper Slate division of the sediments at English Lake, near Penokee Gap. The most crystalline part of this Upper Slate member runs from Penokee Gap westward, and here the basal member of the Keweenawan, lying north of it, is a great mass of gabbro. The lower members of the Upper Slate at Penokee Gap, although at lower horizons, and therefore presumably more deeply buried, and moreover containing unquestionable intrusions of the diabase, are nevertheless composed of comparatively little metamorphosed black slate. It seems conclusive that these mica-schists in the vicinity of Snowbank Lake and those occurring in Penokee Gap both owe their present characters to the alteration of an original slate by the gabbro.

At a point only a few miles west of Montreal River, and again at the top of the Upper Slate member, near the gabbro, the rock is a gray, coarse, strongly micaceous graywacke, the only recognizable clastic material in the rock being the coarse quartz and feldspar. In Michigan, on the Penokee-Gogebic range, east of Montreal River, the bottom members of the Keweenawan are comparatively thin-bedded lava flows, dolerites, and

[a] Mon. U. S. Geol. Survey Vol. XIX, 1892, pp. 302–308.

amygdaloidal lavas, and here the top layers of the Upper Slate are the ordinary or slightly metamorphosed black slates. From this it appears clear that on the Penokee range the metamorphism of the slates and mica-schists is due to the gabbro, and the same conclusion seems to follow for the similar schists in the Vermilion district.

The Lower Huronian slates appear at a number of places on the north, south, and southeast shores of Gobbemichigamma Lake. On the southeast and east shores these slates are in many places found in direct contact with the Keweenawan gabbro, and where near it or in contact with it they have been extremely metamorphosed. Much less metamorphism is noticeable on the slates occurring on the north side of the lake. That part of the south shore of the lake in the immediate vicinity of the section line between sec. 1, T. 64 N., R. 6 W., and sec. 6, T. 64 N., R. 5 W., affords a good opportunity for studying the relations between these two rocks. There is a high cliff at the point where the section line above mentioned comes to the shore. On this cliff one can readily detect bands of rock which strike N. 10° E. magnetic and dip 20° to the east. This strike as taken really represents the strike of the face of the cliff. Were it possible to obtain it, the true strike of the beds would be found to be somewhat different. The bands in the cliff are made up of very dense-grained, hard, siliceous rock. They are rarely more than 4 inches in thickness and frequently very much thinner. Alternating with these bands there is a rotten, brown, coarse-grained material which seems to weather very readily—it certainly does so in comparison with the adjacent harder bands—and appears much like gabbro. If we follow the shore around to the northeast it is there possible to land and ascend the sloping hill leading to the top of the above-mentioned cliff. In the ascent of this hill one crosses the bands of rock, which are imperfectly shown in this section. The harder bands are especially recognizable, as they are likely to form shelves, the slopes between being formed of the softer gabbro-like material. The relations here seem to indicate either that the banded sedimentary has been included in the gabbro or else that the gabbro has been thoroughly injected into the sedimentary, the injection following chiefly the bedding planes as planes of least resistance. The normal coarse-grained gabbro occurs on the shore just a short distance—about a quarter of a mile—back of this headland. Following this shore from the cliff to the west we note appearing at the water level a conglomeratic looking rock, the pebbles of which seem to be a dense quartzitic graywacke or slate, whereas the matrix is light colored, rather coarse grained, and appears like an exceedingly feldspathic biotite-gabbro. This conglomeratic rock is cut by a sheet of basalt 12 to 16 inches wide, which is very nearly horizontal, showing only very slight east-west rolls. The basalt sheet is separated into very symmetrical hexagonal columns, and shows a distinct fine basalt selvage, while at its center the sheet is coarser grained. Ascending the cliff, above this conglomeratic rock, we pass from it into a coarse brown, more or less friable rock, which calls to mind Winchell's muscovado. Still higher up this rock is found to grade vertically into a coarse normal gabbro. This conglomeratic-looking rock continues along the shore still farther to the southwest.

Following the shore of Gobbemichigamma Lake to the east of our starting point at the cliff, a pseudo-conglomeratic rock similar to that described above begins on the shore just a little north of the meander corner of the town line between Ts. 64 and 65 N., R. 5 W. The rock here is rather fine-grained granular rock, weathering white to yellow and brown, in which occur very frequent rounded areas all essentially alike and seemingly of one kind of rock—a dense, green, fine-grained very quartzose graywacke. A similar rock is well exposed on the little island just west of the shore on which the meander corner stands, and here also its relations to the gabbro and its true characters are better shown than elsewhere. The occurrence observed here has already been described (p. 343). The gabbro is evidently younger than the pseudo-conglomeratic rock, which has, in fact, been produced from preexisting sedimentary rocks by the intrusion into them and extensive metamorphism of them by the gabbro.

SECTION II.—ACID AND BASIC INTRUSIVES OF THE LOWER HURONIAN.

INTRODUCTION.

In Section III of Chapter III various acid intrusives which are of the same general petrographic character and geologic age are discussed. In addition to these intrusives, there are found in the Vermilion district three other large masses of granite and granite-porphyry, from which numerous dikes have been given off. These large masses and accompanying dikes penetrate the surrounding Lower Huronian sediments and other adjacent rocks. The large masses especially have produced on the adjacent rocks far-reaching metamorphism. In addition to these main areas and the dikes which can be connected with them, there are throughout the district acid dikes which vary somewhat in petrographic characters and which penetrate the various formations adjacent to them. The largest masses of these acid rocks occur in the core of the Giants range, in the vicinity of White Iron Lake, extending northeast and southwest of that area, and in the vicinity of Snowbank and Cacaquabic lakes, and are described below. In addition, a section will be devoted to a brief description of the various dikes which can not properly be connected with these masses, but are assumed to be of essentially the same age. Still another section is given to a very brief description of certain basic and intermediate dikes which have been found to bear the same relations to the adjacent formations as the acid intrusives bear, and which are hence presumed to be of the same age.

GIANTS RANGE GRANITE.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Distribution.—The Giants Range granite borders a portion of the southern side of the Vermilion district, and is best developed in that part of the area extending from the vicinity of Beaver River, in secs. 31 and 32, T. 62 N., R. 13 W., eastward into secs. 24 and 25, T. 63 N., R. 10 W. Immediately in the vicinity of White Iron Lake it reaches a very extensive development, and to the southwest, in the portion of the Giants range in the Mesabi district, it occupies the core of the range, and here shows its typical characters, and has therefore been called the Giants Range granite. The granite underlies a very much greater area than is shown on the map (Pl. II). According to the Minnesota maps, and also as observed in a reconnaissance trip, it extends a number of miles to the south of the area here described, where it is bordered by the Duluth gabbro mass. This gabbro mass likewise cuts across it in the northeast-southwest direction, gradually nearing the area underlain by the granite as it is followed eastward, until in sec. 19, T. 63 N., R. 9 W., the granite is completely cut out by the gabbro. The area underlain by this granite thus varies from a very narrow strip on the east, where it actually feathers out, to an area 5 or 6 miles across, at a point south of White Iron Lake. The portion in the area described in this report is rarely more than 2 miles wide and usually less than that. Indeed, that part of the granite which was actually studied represents merely the border of the granite, for the reason that in most cases our traverses were ended at the northern border, as the prime object of the survey was the delimitation and study of the formations in the iron-bearing district proper.

Exposures.—The exposures of granite are good, as the area in which it lies is well dissected by streams and contains a number of lakes. The exposures are especially good on White Iron Lake, in T. 62 N., Rs. 11 and 12 W.

Topography.—The topography is that usually seen in the granitic areas of the Lake Superior region, consisting of low rounded to oval hills with lakes here and there in the intervening valleys. The range of hills formed by the Giants Range granite is the topographic continuation to the northeast of the Mesabi or Giants range of the Mesabi district. The hills are nowhere high, however, and do not show very well the character of a hill range.

About 2 miles southeast of Ely and extending from sec. 11, T. 62 N., R. 12 W., to sec. 25, T. 62 N., R. 13 W., there is an area underlain by this granite which is very similar to that occurring north of the district on Iron Lake (see p. 259). This area is almost base-leveled, the lakes into which it is drained representing the level to which the surrounding land has been very nearly reduced. This area is very much larger than that occurring near the international boundary before referred to. Here the swamps are extensive and the elevations are very slight, being flat hillocks of granite rising as a rule only a few feet above the adjacent low ground.

PETROGRAPHIC CHARACTERS.

Macroscopic characters.—The Giants Range granite includes a series of granites ranging in color from light gray to very dark gray, to flesh color, pink, and red. The grain varies also very materially, the rock passing from very dense fine-grained granites through medium to coarse-grained ones. While this rock is, as a rule, granitic in texture, there are also variations to granite-porphyries and exceptionally to some that can be spoken of as rhyolite-porphyries. These granite- and rhyolite-porphyry dikes are normally found cutting the greenstone which borders the Giants Range granite on the north. They are described with the Giants Range granite, since they are presumed to be offshoots from it, although their direct field connection with it can not be shown. Their petrographic similarity to the main granite mass seems alone sufficient to warrant their description together and to support the view that they were derived from the same deep-seated source.

In places along the Kawishiwi River the granite is slightly schistose. This schistosity is especially noticeable along the margin of the granite, where it lies next to the Archean Ely greenstone. These schistose phases can be well seen in the southern half of sec. 24, T. 63 N., R. 10 W., immediately north of the Kawishiwi River.

The granite massive includes areas of dark hornblende and mica rocks which are more or less schistose and consist of hornblende, mica, quartz, and feldspar in about equal proportion. The relationship which the granite is presumed to have to these is indicated by the use above of the word "includes," for it surrounds these masses in some cases and sends offshoots into them. In other cases the granite is found cementing an eruptive breccia the fragments of which were derived from the above-mentioned schists. Such a breccia, for example, is well shown just north of Clearwater Lake, alongside the portage entering that lake from the Kawishiwi River. These fragments in the granite are in some cases derived from the Ely greenstone. In other cases the fragments represent a sedimentary series, the Lower Huronian, which has been intruded and included by the granite. It is difficult to determine the original characters of these included rock fragments from a microscopic study after they have been metamorphosed. In the field one has as a guide the proximity of the granite to larger masses of metamorphosed sediments on the one hand or to the Ely greenstone on the other. Naturally the fragments in the granite are most likely to have been derived from that rock to which the fragments are nearest.

Dikes of very fine-grained red aplite cut the Giants Range granite.

The constituents of these granitic rocks as disclosed by the microscope are orthoclase (microcline), plagioclase, quartz, hornblende, mica, zircon, apatite, sphene, a little iron ore. These minerals possess their usual characters. It is interesting to note that the microcline is especially abundant in granites which show the pressure effects in the other minerals more evidently than the rocks with a smaller amount of the microcline. This is evidence in favor of the microcline twinning having been produced by pressure. The quartz and feldspar occasionally are in micropegmatitic intergrowths. Some secondary minerals occur with these rocks, such as chlorite, sericite, and epidote.

RELATIONS TO ADJACENT FORMATIONS.

The Giants Range granite is found at different places in juxtaposition with the Ely greenstone, the Soudan formation, the Lower Huronian sediments, and the Keweenawan gabbro, enumerated in order from the base up. Its relations to these formations are in each case quite clearly shown and will be specifically described in the following paragraphs.

Relations to the Ely greenstone.—The granite cuts the greenstones constituting this formation in innumerable dikes which individually seem to have little effect upon the greenstone, judging from the lack of well-marked contact zones adjacent to the dikes. As we get nearer the contact between the greenstone and the granite massive, however, exactly the same kind of metamorphic products are observed as are found associated with the contact of the intrusive granite of Trout, Burntside, and Basswood lakes with the Ely greenstone on the northern side of the district. As the dikes increase in number the greenstones are altered to amphibolitic and micaceous schists, frequently still retaining the unmistakable amygdules and ellipsoidal parting of the original greenstones. Similar products of the granite intrusion have been described under the description of the effect of the granite of Trout, Burntside, and Basswood lakes on the Ely greenstone (p. 156 et seq.).

Relations to the Soudan formation.—The Soudan formation is, as has been stated, of very limited extent, and consequently there are few opportunities for observing granite dikes in it. However, such dikes have been observed at a number of places (see p. 359), and their presence shows clearly that the Giants Range granite cuts the Soudan formation and is hence younger than it.

Relations to the Lower Huronian sediments.—The Duluth and Iron Range Railroad, south of Tower, especially in the vicinity of milepost 92, gives very good sections through the Lower Huronian sediments and shows them to be cut by dikes of granite. These dikes vary in size on different exposures, ranging from 1 inch up to 4 feet in width. They can not be connected in the field directly with the granite dikes which cut the gray Embarrass granite,[a] lying a number of miles to the south, but their general characters are so similar that they are presumed to be of the same age as these dikes, and to have been derived from the same source. Moreover, farther east practically the same granite is found in dikes which are clearly offshoots from the Giants Range granite, and those at the extreme western side of the district are likewise supposed to be offshoots connected underground with the Giants Range granite mass, although at the surface they are a good many miles distant from it. The metamorphosing effect of the Giants Range granite on these sediments has been described under the description of the sediments themselves (pp. 340–341).

As we go northeast in the district beyond White Iron Lake, especially along the Kawishiwi River, we find a comparatively small area of sediments, conglomerates, graywackes, and associated slates extending from near the mouth of the Kawishiwi River on Farm Lake, sec. 34, T. 63 N., R. 11 W., eastward into sec. 29, T. 63 N., R. 10 W. The area underlain by these sediments has a north-south extent from the Kawishiwi River to Clearwater Lake of about 1½ miles. These rocks are identical petrographically with the rocks which have been classed with the Lower Huronian sediments and are presumed to be of the same age. They are cut through and through by dikes of the Giants Range granite, and as a result of this intimate intrusion they have been metamorphosed to their present condition of mica- and hornblende-schists and gneisses.

Relations to the gabbro.—Within the limits of the map (Pl. II) the Giants Range granite and the great Keweenawan gabbro are in proximity to each other only along the Kawishiwi River, from sec. 34, T. 63 N., R. 10 W., to sec. 19, T. 63 N., R. 9 W. Although the area lying within the map in which the granite and gabbro lie close together is small, nevertheless the relations between the two rocks are sufficiently clear. The gabbro lies obliquely across the northeastern continuation of the Giants Range granite and even overlaps the Archean greenstones and the Lower Huronian sediments, which lie north of the granite. The way in which these rocks are interrupted in their eastern continuation indicates an eruptive relationship of the gabbro to them. Moreover that this is the true relationship between

[a] The Mesabi iron-bearing district of Minnesota, by C. K. Leith: Mon. U. S. Geol. Survey Vol. XLIII, 1903, p. 186.

the gabbro and the Giants Range granite is conclusively shown by the presence of a dike of gabbro which occurs in the Giants Range granite upon the portage at the falls of the Kawishiwi, in sec. 19, T. 63 N., R. 9 W. This dike was not directly connected with the gabbro, but is macroscopically the same and is only about a quarter of a mile away from the contact line between the gabbro and granite massives. Attention may be called to one further fact indicative of the intrusion of the granite by the gabbro, and that is that the Giants Range granite near its contact with the Duluth gabbro appears a little more basic than elsewhere, and approaches the gabbro somewhat in general appearance. Thus the granite is found to contain some augite. There seems in many places to be a transition between these two rocks, although ordinarily the contact is sharp. The transition rock is in a few places broken into round masses and these are cemented together by a schistose chloritic material. One might conceive of such a transition phase being equally likely to result from the intrusion of the granite into the gabbro. However, the above-mentioned dike seems to clinch the relationship existing between these two rocks.

AGE.

From the preceding statement of facts concerning the relation of the Giants Range granite to the adjacent rocks, we are enabled to draw the conclusion that the granite was intruded after the Lower Huronian sediments were deposited and before the intrusion of the Duluth gabbro of Keweenawan age.

FOLDING.

As has been already intimated, the granite shows very slight effects of crushing or of the action of mountain-building forces, but that it has been exposed to a certain amount of pressure is clearly shown. Small granite dikes cut through the adjacent greenstone areas and lie parallel to the schistosity of the greenstones. They were probably intruded subsequent to the production of this schistosity, and hence followed along the planes of easiest parting, which were the planes of fissility in the rock. Subsequent to their intrusion these granite dikes have, however, been squeezed, for we find that occasionally they have been broken into pieces and these broken portions have been separated, and, in fact, in some cases even the fragments of the dikes have been rounded until they have acquired a more or less lenticular shape. These effects are probably due to minor folding, which has taken place subsequent to the period when the schistosity was produced and the granite intruded, this second period of folding having, indeed, emphasized the schistosity due to the first period of folding and having slightly affected the Giants Range granite.

METAMORPHIC ACTION OF THE GIANTS RANGE GRANITE.

The metamorphic effect of this granite on the greenstones being essentially similar to that produced by the intrusion of the granite of Trout, Burntside, and Basswood lakes will not here be discussed, the reader being referred to the previous discussion for the details and results of the process.

As a result of the intrusion of the Giants Range granite, the Lower Huronian sediments have also been extensively metamorphosed. A discussion of this metamorphism may be found under the discussion of these sediments (p. 340).

INTERESTING LOCALITIES.

Relations to the Archean Ely greenstone.—The relations of the Giants Range granite to the Ely greenstones are well shown in the SE. $\frac{1}{4}$ of sec. 24, T. 62 N., R. 13 W., and in the NW. $\frac{1}{4}$ of sec. 19, T. 62 N., R. 12 W.

Relations to Soudan formation.—Dikes of the Giants Range granite have been observed cutting the Soudan formation at several places; for instance, at 200 paces west of the southeast corner of sec. 7, T. 62 N., R. 12 W., the iron formation is cut by injections of granite which run parallel to the bands of the iron formation. Dikes of the same granite cut the adjacent Ely greenstone just north and west of this locality. At 1,050 paces north, 550 paces west of the southeast corner of sec. 28, T. 62 N., R. 13 W., the iron formation is likewise cut by granite dikes. Similar dikes cut the iron formation in secs. 3 and 4, T. 62 N., R. 12 W. These dikes can be well observed at the places where they occur on the bare hills south of Ely. In this particular instance the dikes are only a very short distance away from the edge of the main mass of Giants Range granite, and that they are offshoots from it can hardly be doubted.

Metamorphism caused by granite.—Reference has already been made to the fact that the Giants Range granite has had an important metamorphosing effect on the rocks which it has intruded. Its effect upon the Lower Huronian slates is well shown in the area south of the Kawishiwi River, in sec. 31, T. 63 N., R. 10 W., and in sec. 36, T. 63 N., R. 11 W. In fact, at a great number of places in this area a traverse almost anywhere will show it. The granite dikes occasionally occur near the river, but become more and more numerous as one proceeds southward and approaches the contact of the main mass of granite. For the most part the sedimentary character of the rocks can not be readily recognized, as they have already been metamorphosed into hornblende- and mica-schists. At one place on the portage leading southeastward to Clearwater Lake, proof of the sedimentary character of these rocks may be seen. They are well-banded amphibole- and mica-schists, but a few bands having a distinctly conglomeratic nature were observed, although even these fine-grained conglomerates are now schistose and carry a good deal of mica, evidently of secondary origin. Farther south the granite dikes become more numerous and the metamorphism more extreme, so that practically the banding and the connection with the rocks showing unquestioned clastic characters are the only indications of the sedimentary nature of these rocks.

The intrusive relations which the Giants Range granite bears to the Ely greenstone are shown at a great number of places in that portion of the Vermilion district adjacent to the area underlain by the Giants Range granite. It is hardly necessary to enumerate the places at which offshoots from this granite penetrate the adjacent greenstone, as they may be found at almost any place in the portion of the area outlined in which large exposures exist. Numerous dikes of the Giants Range granite have been found in nearly every place where its contact has been followed. Many of them are indicated upon the accompanying map (Pl. II), but it has been found impossible to show all of those which have been found. Numbers of them were seen in secs. 24, 27, and 28, T. 62 N., R. 13 W. Many others occur in secs. 7, 8, 17, 18, and 19, T. 62 N., R. 12 W., and they are especially easy to find on the bare hills southeast of Ely, in secs. 1, 2, and 3, T. 62 N., R. 12 W. A number of such dikes cut the hills south of Pickerel Lake, along the line between sec. 25, T. 63 N., R. 11 W., and sec. 30, T. 63 N., R. 10 W. The bold hills on the north shore of the Kawishiwi, in secs. 20, 28, and 29, show a number of these dikes penetrating the greenstones. Others, in considerable number, may be found on the hills north of Stone Lake, in secs. 16, 17, 20, and 21, T. 63 N., R. 10 W. A number of others likewise occur in secs. 10, 14, and 15, T. 63 N., R. 10 W., and at a number of places which it is not necessary to enumerate. Throughout this part of the district the relation of the granite to the greenstone, which is shown not only by the presence of these dikes but also by the effect of the granite on the greenstone, may be seen, if strict attention is paid to the changes which take place, as the granite is approached from the north. In every instance where the exposures are sufficiently numerous, as, for example, in the vicinity of Ely, it will be seen that the greenstone changes its character, becoming more and more schistose, and finally passing into marked amphibole- and mica-schists in close proximity to the granite.

SNOWBANK GRANITE.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

The Snowbank granite has received its name from the fact that it is typically developed around Snowbank Lake, which covers several sections and parts of sections of T. 64 N., Rs. 8 and 9 W., and T. 63 N., R. 9 W. The granite is confined exclusively to the immediate vicinity of the lake, being best developed on the southern shores of the lake and on the islands in that portion of the lake.

The exposures are very numerous and excellent. Although the granite occupies the center of a structural anticline, it nevertheless does not emphasize this structure by forming an area of topographically higher ground than that of the surrounding country. The topography is not of marked character, having the usual rounded gentle contours so common in the glaciated granite areas of this district.

PETROGRAPHIC CHARACTERS.

The granite occurs in good exposures in the vicinity of the shores of the lake, where its characters may be easily studied. It is predominantly pink to red in color, although on fresh fracture it is a gray or flesh-colored rock. Some facies, however, are much darker colored, as the result of a higher content of the dark minerals than is contained in the normal granite. The granite varies from the fine-grained to the coarse-grained form, the medium-grained facies being most abundant. Porphyritic facies of the granite also occur, but are not very abundant. The porphyries are developed as granite-porphyries and microgranite-porphyries with feldspar, augite, and quartz phenocrysts in a fine-grained groundmass. These porphyries, as well as the very fine-grained granites, occur chiefly as offshoots from the main medium-grained mass, and penetrate the sediments which surround the granite massive.

Mineralogically the Snowbank granite varies from a normal mica- and hornblende-granite to an augite-granite, and, by loss of quartz, to a syenite. The hornblende-granites are invariably much darker than the mica-granites. These last tend to reddish colors, while the hornblende-granites are usually dark gray or red if the orthoclase is very prominent and considerably weathered. As the green augite takes the place of the hornblende, these hornblende-granites pass over into the augite-granite. The augite-granite is a grayish, flesh-colored to red medium-grained granite, and does not differ materially from the normal Snowbank mica- and hornblende-granite in macroscopic appearance. The red augite-granite has been observed to cut the normal Snowbank granite, as for instance on the point projecting northeastward from the mainland and forming the NW. ¼ of the SW. ¼ of sec. 36, T. 64 N., R. 9 W. Here the medium-grained red augite-granite cuts a hornblende-syenite phase of the Snowbank granite, and is in its turn cut by a basalt dike. This red augite-granite is also reported to be cut by the hornblende-granite[a] Both observations are correct, the explanation, as it appears to me, being that they are of essentially the same age and are differentiation products of the same magma. For this reason they are included here together as constituting the Snowbank granite complex.

No attempt has been made to discriminate on the map between the normal mica-granite, the hornblende-granite, and the augite-granite. They show nothing of peculiar interest under the microscope. The normal combination is mica, quartz, and feldspar, both orthoclase and plagioclase, with some iron oxide in very small quantities. Hornblende is commonly found with the mica, and as it increases in quantity the rock passes to a hornblende-granite. Usually a great deal of sphene is present in the hornblende-granite, and it is more prominent in the hornblende-syenites, which are connected with the hornblende-granites and differ from them only in containing very much less or practically no free quartz. Augite accompanies the hornblende in some of the hornblende-granites, and as it increases in quantity and the hornblende diminishes there is the gradation to the augite-granite.

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, pp. 427–428.

RELATIONS TO ADJACENT FORMATIONS.

Relations to the Lower Huronian.—The Snowbank granite is found in contact with the adjacent Lower Huronian sediments, both the Ogishke conglomerates and the Knife Lake slates. In a number of places dikes, offshoots from this mass, occur in the adjacent sediments. Moreover, the sediments near the granite have been very much changed. They are full of mica in relatively large crystals, and in general the rocks have been recrystallized until they are now in places mica-schists. The crystalline character of these rocks is most noticeable near their contact with the main granite mass and at places where they are cut through by numerous dikes of the granite and where the fragments of the sediments are inclosed in the dike rocks. The farther away from this contact we go the less numerous the dikes become and the less pronounced are the indications of metamorphism until, at a distance varying in places from half a mile to a mile, the sediments seem to show their normal character. The presence of the dikes in the sediments and the contact effect of the granite on the sediments clearly show the intrusive character of the granite. The facts referred to briefly above were observed and recorded in their notebooks by the members of the Minnesota survey, but the interpretation given to these facts by the State geologist[a] is very different from that given above. According to him the Snowbank granite is a product of the metamorphism of acid sediments, graywackes, and conglomerates, and the granite and granite-porphyries are connecting links showing transitions to the sediments. The complete fusion of these graywackes produced the granite. Incomplete fusion accounts for the metamorphosed sediments surrounding the granite massive. The dikes in the sediments at some distance from the border of the granite are portions of the molten sediments which penetrated the unfused ones.

Relations to the Keweenawan gabbro.—The granite has not been found in actual contact with the large mass of Duluth gabbro lying south of and next to it. Along the contact there is a slight topographic break, occupied by low ground, in which exposures are wanting. The granite is of Lower Huronian age, and there can be no doubt that the Duluth gabbro is younger than it is. However, if the gabbro exercised any

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, pp. 287–294.

metamorphic effects upon the granite, they have not been observed, nor have any dikes that could be traced to the gabbro been found cutting through it.

INTERESTING LOCALITIES.

The best portion of the area in the vicinity of Snowbank Lake in which to study the relations of this granite to the adjacent sediments is east of the lake, in general between its outlet and Disappointment Lake. In this area the hills are bare, and good exposures are numerous. A number of good exposures can be found on the shores of Snowbank Lake north and south of its outlet, and here the Snowbank granite is found cutting the adjacent conglomerates in numerous dikes. These same relationships may be found still farther inland, on the hills in the area to which reference has already been made. Other exposures showing the same relations may be found at almost any place along the north and northwest shores of the lakes, and a traverse inland from these shores will almost invariably result in the finding of dikes cutting the adjacent schist. There is nothing especially peculiar in the relations of these dikes to the rocks which they cut or in the occurrence and appearance of these dikes, consequently no detailed enumeration of them will be given.

CACAQUABIC GRANITE.

This granite occurs typically on the islands in and the shores of Cacaquabic Lake, from which it was named by the Minnesota survey. It has been more or less extensively studied by the Minnesota State geologist and his assistants, and mention and description of it occur in a number of the State reports.[a]

U. S. Grant has made an especially detailed study of this granite,[b] and as a result of his careful mineralogic and chemical analyses has determined it as one of the comparatively rare augite-soda granites. Studies of the Cacaquabic granite corroborate in the main the statements of Grant, but there has been no opportunity to make detailed mineralogic studies or chemical analyses of the rock, and data resulting from these have been obtained from Grant's articles, to which reference has been made.

[a] Geol. and Nat. Hist. Survey of Minnesota, Fifteenth Ann. Rept., 1886, pp. 361–369; Sixteenth Ann. Rept., 1887, pp. 149–156; Twentieth Ann. Rept., 1891, pp. 70–79; Twenty-first Ann. Rept., 1892, pp. 5–59, 2 plates. Grant, U. S., Am. Geologist, Vol. XI, 1893, pp. 383–388; Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, pp. 294, 442, and 450; Final Rept., Vol. V, 1900, descriptions of sections in various places.

[b] Loc. cit.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

The granite is confined in its distribution to the immediate vicinity of Cacaquabic Lake, and is especially well developed on the southern side. It extends back from the lake for a maximum distance of about a mile, reaching down into the SE. $\frac{1}{4}$ of secs. 1 and 2, T. 64 N., R. 7 W. The granite occupies on the whole higher ground than is occupied by the adjacent rocks, forming, especially in secs. 1 and 2, fairly high hills. There are excellent exposures on a number of islands in the lake and also on the mainland near the shore.

PETROGRAPHIC CHARACTERS.

The Cacaquabic granite, like the other granite complexes of the Vermilion district, shows considerable variation both in texture and mineralogic composition. The main mass of the granite is a medium-grained gray or pink to red rock, whereas on the periphery of the granite area the finer-grained and granite-porphyry facies are developed.

The granite-porphyry facies contains large phenocrysts of plagioclase feldspar lying in a fine-grained gray to red groundmass. The phenocrysts themselves range from gray to red in color, depending on the degree and the character of the alteration. When red in part or as a whole, the phenocrysts give the granite-porphyry a very striking appearance. They then stand out prominently from the lighter-colored groundmass. In general there seemed to be no arrangement of the phenocrysts, but in one case the phenocrysts of the granite-porphyry did show a distinct parallelism of their major dimensions. There was thus produced a more or less perfect macroscopic flowage structure.

The granite and granite-porphyry are massive, although in places much jointed and separated into small blocks by the joint planes. In places[a] the fractures in the granite are filled by veins of infiltrated quartz.

Mineralogically the granite varies considerably. While the main mass is an augite-soda granite,[b] an examination of the specimens collected shows variations to a hornblende-granite and hornblende-mica-granite. Grant reports an augite-biotite-syenite facies.[c] The minerals constituting the

[a] The Geology of Kekekabic Lake, by U. S. Grant: Geol. and Nat. Hist. Survey of Minnesota, Twenty-first Ann. Rept., 1892, pp. 34–36.

[b] Loc. cit., p. 33.

[c] Loc. cit., p. 50.

granite are quartz, feldspar (both orthoclase and plagioclase), augite, hornblende, mica, sphene, apatite, magnetite, and hematite. The phenocrysts are of plagioclase. Most of the minerals have their normal characters and will not be described. The feldspar and augite are somewhat exceptional, and have been described in detail by Mr. Grant,[a] from whose description the following details concerning these are taken.

Grant's study of the feldspar shows that the plagioclase has a specific gravity ranging from 2.58 to 2.62 and the chemical composition shown below.[b]

Analysis of feldspar of Cacaquabic granite.

	Per cent.
SiO_2	67.99
Al_2O_3	19.27
Fe_2O_3	.82
CaO	75
MgO	.02
K_2O	3.05
Na_2O	6.23
H_2O	.90
Total	99.03

From this he concludes that the feldspar is an anorthoclase composed of orthoclase, albite, and anorthosite molecules in the following proportions: Or_5, Ab_{14}, An_1.

The augite varies from a colorless one to a variety having a bottle-green color. The colorless kind is not uncommonly intergrown with the green variety. Sometimes this is in zonal intergrowth. The individuals possess a very good crystallographic development. The specific gravity of the augite as a whole is somewhat higher than 3. An analysis of the augite given by Grant is here quoted:

Analysis of augite of Cacaquabic granite.

	Per cent.
SiO_2	53.19
Al_2O_3	2.38
Fe_2O_3	9.25
FeO	5.15
CaO	17.81
MgO	9.43
K_2O	.38
Na_2O	2.63
H_2O	.01
Total	100.23

[a] Geol. and Nat. Hist. Survey of Minnesota, Twenty-first Ann. Rept., 1892, pp. 47–48. [b] Ibid., p. 44.

Assuming that this represents an isomorphous mixture of the diopside, hedden-bergite, acmite, and fassaite molecules, and calculating their relative proportions, we get approximately the following result:

	Per cent.
Diopside, Mg Ca Si_2O_6	47
Heddenbergite, Ca Fe Si_2O_6	27
Acmite, Na Fe Si_2O_6	21
Fassaite, Mg Al_2SiO_6	5

In the considerable percentage of the acmite molecule this augite approaches in composition the pyroxene of the more alkaline rocks, the eleolite syenites. This analysis very probably represents quite well the usual composition of the green augite, as the proportion of zonal crystals, with colorless centers, and entire colorless crystals, is small. The colorless augite is very similar to that of the well-known augite granite from Laveline in the Vosges.

The analyses of the anorthoclase feldspar and of the augite which are quoted above show such a proportion of sodium oxide that one would expect the granite itself to exhibit a very high ratio of that substance. This proportion is shown in the following analyses,[a] I being that of the normal Cacaquabic granite facies as given by Grant, and II being that of the granite-porphyry facies.

Analyses of Cacaquabic granite and granite-porphyry.

	I.	II.
	Per cent.	Per cent.
SiO_2	66.84	67.42
TiO_2		
P_2O_5	Tr.	0.07
Al_2O_3	18.22	15.88
Fe_2O_3	2.27	1.37
FeO	0.20	1.14
MnO		Tr.
CaO	3.31	3.49
MgO	0.81	1.43
K_2O	2.80	2.65
Na_2O	5.14	6.42
H_2O	0.46	0.05
Total	100.05	99.92

[a] Loc cit., p. 41.

Secondary minerals, such as sericite, chlorite, and hornblende occur abundantly in some of the rocks. The rocks have locally been crushed, but the crushing has in no case reached such a degree as to produce schistose rocks, although the microscope shows crushing effects reaching even to the granulation of the quartz. The microscopic fractures are healed by quartz and feldspar and also by hornblende when the fractures cross a hornblende individual. In such a case one can readily distinguish the secondary needles of nearly colorless hornblende which traverse the fractures and unite the pieces of the old massive green hornblende individual.

RELATIONS TO ADJACENT FORMATIONS.

Relations to the Lower Huronian.—The Cacaquabic granite lies adjacent to the Lower Huronian sediments, which very nearly surround it. In the area in which the sediments are wanting the gabbro lies next to the granite. The relations of the granite to the adjacent formations are not nearly so clear here as were the relations described for the Snowbank granite. The granite contains dark-colored chloritic basic inclusions which may have been brought up from the Archean greenstone that underlies the sediments, an anticline of it lying a short distance southeast of the granite, and another north of it. The Cacaquabic granite grows finer grained as the mantle of sediments is approached, and it has been found, moreover, cutting the sediments in dikes which show clearly that it is intrusive in them and of younger age. If it has metamorphosed them, as is probably the case, its metamorphism is concealed by the later metamorphism caused by the gabbro.

Relations to the gabbro.—The statement that the gabbro is later than the granite is not warranted by any actual contacts that have been found between them, or by the occurrence of any inclusions of the granite in the gabbro, but is based chiefly on their field relations, shown on the accompanying map, and on the comparatively youthful age of the gabbro. Thus it will be seen that the granite everywhere, except on the southeastern edge, is surrounded by the sediments. Presumably it was originally completely surrounded by them; but for this narrow area, however, the gabbro has cut out the sediments and overlaps on the area underlain by granite.

AGE.

It will thus be seen that the Cacaquabic granite massive is an intrusive of younger age than the Knife Lake slates, but older than the Keweenawan gabbro.

INTERESTING LOCALITIES.

At only two places has the granite been found showing its relations to the adjacent sediments. One of these places is 700 paces north, 650 paces west of the southeast corner of sec. 1, T. 64 N., R. 7 W., south of Cacaquabic Lake, where the sediments are cut by dikes of the granite. The other point is just back of the southwest shore of Cacaquabic Lake south of a large granite island. Here the porphyritic form of the granite cuts the adjacent conglomeratic sediments.

Still other dikes occur in the southeast corner of sec. 1, T. 64 N., R. 7 W., on the hills north of the small lake in which the four sections which meet at this place have their corner.

VARIOUS ACID DIKES.

Certain acid dikes, to which reference has already been made, are found cutting through the various formations of the district, but can not be directly connected with any of the large eruptive masses. They are presumed to be of Lower Huronian age, and the evidence for this will be given on another page, yet it is possible that some of them may be of Keweenawan age, although if there are any Keweenawan dikes included among them, they can not be recognized as such on account of lack of evidence. They are not of sufficient interest or importance, however, to warrant a description of the individual dikes; consequently an attempt will be made to give merely a general idea of their characters.

DISTRIBUTION.

The distribution of these dikes will be seen on the maps in the accompanying atlas, on which they are marked with the same symbol and the same color as that used for the Giants Range, Snowbank, and Cacaquabic granites. In most cases the exposures of these dikes are small, so that in many instances it is practically impossible to state absolutely that they are younger than the rocks near them. This presumption, however, is warranted by the occurrence of these other rocks which surround them in numerous exposures. They are of such small areal distribution that they do not materially influence the topography in general, although, since they are generally harder than the rocks through which they cut, they do exert a local influence and are found forming knolls or ridges.

PETROGRAPHIC CHARACTERS

Macroscopic.—These dikes vary in grain from very fine-grained, almost cryptocrystalline rocks, to those which may be classed as coarse-grained ones. Moreover, a porphyritic structure is of very common occurrence, the quartz being sometimes the sole phenocryst though at other times both quartz and feldspar occur as phenocrysts. In color there is likewise considerable variation. For the most part the rocks are gray to pink on fresh fracture. Some of the finer-grained ones, however, are dark purplish. The weathered surfaces are nearly always pink to reddish. The dikes vary greatly in width. They are usually narrow, but some dikes as much as 10 feet wide have been observed, and the grain usually varies with the width, the finer-grained rocks occurring in the narrower dikes and as the selvage of the wider ones.

Microscopic.—Under the microscope one can recognize phenocrysts of green hornblende in association with phenocrysts of feldspar and quartz. The quartz is relatively scarce. These phenocrysts lie in an exceedingly fine-grained groundmass with, in some cases, grains too small to permit their characters to be recognized. Generally it can be seen that the groundmass is made up of quartz and feldspar, flakes of chlorite and sericite, and some iron ore. Occasionally the grains and flakes are arranged in parallel lines which so bend around the phenocrysts as to bring out a very well-marked flowage texture. All of the minerals have their usual characters, and hence no description will be given of them.

RELATIONS TO ADJACENT FORMATIONS.

It is believed that these acid dikes are offshoots from the various granites described in this chapter. They show a general petrographic similarity to them. Still they are not so much like them as to warrant one in making a positive statement that they are the same. Moreover, they have not been connected in the field, nor have any chemical analyses been made which would enable one to determine their similarity in chemical composition to the adjacent granites. The differences between them, which are textural, can be explained by the fact that these offshoots occur in so much smaller quantity that naturally they would not acquire the same textures as the coarser-grained granites and granite-porphyries of the large massives.

It has already been stated that these acid rocks occur as dikes in the adjacent formations. In some instances their dike character is not clearly shown, actual contacts between them and the rocks occurring nearest to them, and through which they cut, being wanting. From the fact that they are igneous rocks and more or less completely surrounded by other eruptives or by sedimentaries, they are supposed to be intrusive in these. They have been found cutting all of the rocks thus far described from the Vermilion district, those of eruptive as well as those of sedimentary origin, with the exception of the various Lower Huronian granites. They are consequently known to be younger than all of the rocks which they cut. Their relations to the Upper Huronian sediments and to the great Duluth gabbro of Keweenawan age have not been determined conclusively. However, as the result of a reconnaissance in the Keweenawan of the Lake Superior region, it has been found that the Keweenawan is cut by acid rocks. While these have not been connected petrographically with the dikes in the Vermilion district, nevertheless it may be well to suggest the possibility that at least some of the acid dikes in the Vermilion correspond to those which cut through the Keweenawan rocks.

BASIC AND INTERMEDIATE INTRUSIVES OF LOWER HURONIAN AGE.

At various places in the Vermilion district basic and intermediate dikes have been observed cutting the country rock. These can be easily divided into dikes of apparently different age by using as a criterion for this the difference in alteration. This macroscopically determined difference is substantiated by the condition of the rocks as shown by microscopic examination. On the one hand there are certain dikes which are composed of very fresh dolerite and basalt and which show distinct selvages. These cut through all the other rocks of the Vermilion district, including the gabbro. Just outside of the district are dikes identical in character with these and cutting even the acid red rock of the Keweenawan, which itself is known to cut the gabbro. These fresh dikes are clearly of Keweenawan or post-Keweenawan age, and will be described under the heading "Keweenawan" in Chapter VI. On the other hand there are dike rocks which cut all the rocks of Archean and Lower Huronian age, but no definite proof has been obtained that they intrude any of the rocks younger than these. The much greater age of these dikes is shown in their more extensive alteration, indicated macroscopically by their green color, and by the occasional presence of an imperfectly developed schistosity. The original characters of these dike rocks are rarely well enough preserved to enable one to determine positively just the kind of rocks they are. It can be said in general that they are of basic and intermediate character. Some have unquestionably been derived from dolerites and basalts. Others, it is clear, belong to the lamprophyric rocks.

The dolerites and basalts are invariably very much altered. Occasionally a fairly well-preserved ophitic texture may be observed. Usually, however, all textures have been destroyed as the result of orogenic movements, and the rocks have become fairly schistose. They were evidently intruded, however, in the Archean rocks after the latter had been subjected to pressure, as they are found in some cases to have been injected parallel to the schistosity of these rocks. The usual constituents are such as are commonly found in these altered basalts: actinolite, chlorite, apatite, calcite, muscovite, feldspar, a little quartz, sphene, and iron oxides.

The lamprophyric dikes above referred to occur usually in very narrow dikes and while ordinarily extremely altered, nevertheless are generally not so much altered as are the dolerites. These rocks consist of various combinations of plagioclase and orthoclase feldspar, with biotite, hornblende, augite, and iron oxide. The hornblende and augite are the predominant dark silicates. A few serpentinous areas indicate the former presence of olivine. The minerals are so much altered that a trustworthy separation of these rocks into the various divisions of the lamprophyres to which they belong could not be made. There seem to be represented among them, however, chiefly biotite-kersantites, augite-kersantites, and the hornblende- and augite-vogesites. With these there also seem to be some camptonites.

Certain other dikes in the district which were observed were so extremely altered that one could only see that the original rock carried hornblende, but the petrographic position of these dikes could not be determined.

INTERESTING LOCALITIES.

No attempt will be made here to enumerate all the places where these dikes occur. A number of them have been shown in exaggerated size on the accompanying maps. On the west end of Stuntz Island there is a plexus of these basic dikes cutting the Ogishke conglomerate. These dikes run parallel to one another, diverge from one another in places, and at other points cut one another. At one place on the top of the conglomerate ridge just south of the small northwestward-pointing bay, nine dikes essentially parallel and varying in width from 1½ inches up to 6 feet were counted within a distance of 60 feet. These dikes cut right across the fragments in the conglomerate, giving sharp contacts. The jasper fragments in the conglomerate which have been cut by the dikes seem to have been apparently unaltered by them. The dikes themselves are moderately schistose, especially on the edges. The rock of these dikes is extremely altered and appears to have been a dolerite.

Similar dikes can be seen cutting across the granite island just east of Stuntz Island, and still others were seen on the high hill along the shore near the northeast corner of sec. 22, T. 62 N., R. 15 W.

A number of lamprophyric rocks were observed cutting the Ely greenstone, the Ogishke conglomerate, and Knife Lake slates near the center of sec. 17, T. 63 N., R. 9 W. Similar dikes occur on the hill on which Ely is built, northeast of the Methodist church, and also on the greenstone hills on the north side of Long Lake.

CHAPTER V.

THE UPPER HURONIAN (ANIMIKIE).

In the eastern portion of the Vermilion district there has been found overlying the Knife Lake slates and the Ogishke conglomerate where these are present and, where they are wanting, lying immediately upon the Ely greenstone or the granite of Saganaga Lake, a series of sedimentary rocks, of which a considerable thickness is exposed. These rocks belong to the great sedimentary series which is best developed in a very wide area lying along the northwest and north shores of Lake Superior and extending well up into Canada, but which is also well developed in the Mesabi district on the southern slope of the Giants range in Minnesota. To this series the name Animikie, the Ojibway word for thunder, has been given by Hunt[a] from the fact that these rocks are typically developed in the vicinity of the two well-known topographic features of the north shore of Lake Superior, namely Thunder Bay and Thunder Cape.

The Upper Huronian series of the Vermilion district may be readily divided into two facies of rocks which are quite different petrographically. At the bottom of the series occurs an iron-bearing formation, known as the Gunflint formation, consisting of bands of ferruginous carbonates, quartz, magnetitic quartz, magnetitic ore, and augite, hypersthene, hornblende, olivine, grünerite, and magnetite rocks. All of these apparently represent altered forms of some original ferruginous rocks. Above these iron-bearing rocks there occurs a great slate-graywacke formation, known as the Rove slate.

SECTION I.—GUNFLINT FORMATION.

The rocks of this formation are well developed on the north shore of Gunflint Lake, from which their name has been derived. They extend in a belt, shown on the maps in the accompanying atlas, for a number of

[a] The geognostical history of the metals, by T. Sterry Hunt: Trans. Am. Inst. Min. Eng., Vol. I, pp. 331-395; Vol. II, pp. 58-59.

miles to the west of the lake, which is a well-known feature of the international boundary route. Rocks with which these are correlated occur in the Mesabi district, and are there known as the Biwabik formation.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Distribution.—The iron formation has a wide distribution in the Mesabi district, extending through it from end to end. The Gunflint formation can be looked upon as the eastern continuation of the iron-bearing Biwabik formation of the Mesabi district. In the Vermilion district this iron formation has a restricted distribution. The area in which the rocks occur is in places not more than about 200 paces wide, from this spreading out to a width of nearly half a mile. Northeast of Paulson's mine, in secs. 21 and 22, T. 65 N., R. 4 W., there is an east-west tongue of the Gunflint rocks projecting westward into Ely greenstone. About three-fourths of a mile east of Paulson's mine, in sec. 27, T. 65 N., R. 4 W., where a great north-south valley cuts directly across the Gunflint formation, the narrow belt of iron formation joins a wider area of the same rocks, which extends over the greater portion of secs. 23 and 26, T. 65 N., R. 4 W. The Gunflint formation is widest in these sections, its great width being due chiefly to the fact that a fairly wide synclinal fold has here been stripped, leaving exposed an unusually large area of the iron formation. East of these sections, toward the international boundary, the formation thins down rapidly. The northern boundary of the Gunflint formation in this area is marked by the Knife Lake slates and Ogishke conglomerate of the Lower Huronian series, and the Ely greenstone and granite of Saganaga Lake of the Archean. This is the order in which the Gunflint formation comes in contact with these rocks from west to east. This is also the stratigraphic order, passing from the youngest on the west to the oldest on the east, with the single exception of the granite of Saganaga Lake, which intrudes the greenstone.

The southern boundary of the iron-bearing formation over the greater portion of the area in which it occurs is the northern edge of the Duluth gabbro. From the SW. $\frac{1}{4}$ of sec. 26, T. 65 N., R. 4 W., however, the direction of the southern boundary changes. From here it swings northeastward and the Rove slates, which overlie it, begin to appear with a narrow edge of a wedge widening to the east and separating the Gunflint formation from the gabbro.

Exposures.—The exposures in the areas outlined are very good. In all instances they are sufficient to enable one to study the rocks in considerable detail and trace out their continuation without greater difficulty than is offered by the very rough and thickly timbered character of the country.

Topography.—Where the Gunflint formation occurs in sufficient quantity to affect the topography to a noticeable extent, the forms produced in it are fairly characteristic. As the result of the monoclinal southward dip and the differential erosion of the harder and softer layers, a series of ridges are produced which trend about east-west and have very steep northward-facing escarpments with gentle southerly slopes corresponding approximately to the dip of the beds. It may be well to mention here that sills of dolerite lying approximately parallel to the bedding frequently form the top of the larger ridges. This same kind of topography, but in a more marked form, is also developed in the area underlain by the Rove slates, which is adjacent to that in which the Gunflint formation occurs, and will be found described in greater detail elsewhere (pp. 391–392).

About a mile east of Paulson's mine there is one very noticeable topographic feature which is not in agreement with the general topography—a large cross valley, running about north and south, which appears to represent an old pre-Glacial valley formerly occupied, perhaps, by a forerunner of the present Cross River, which flowed through it on its way north into Boundary River and Saganaga Lake.

STRUCTURE.

The structure of the Gunflint formation in that portion which is exposed in the Vermilion district is not very complicated. There is a small northeast-southwest trending area of Gunflint formation rocks exposed on the southeast shore of Disappointment Lake. Here the sediments have a strike corresponding very closely to the trend of the area itself—that is, northeast-southwest—and they dip to the south. In rocks of similar age on Gobbemichigamma Lake the structure is a little bit more complicated. In this case the sediments have been folded, and as a result we now find them forming in the main a syncline plunging toward the northwest, but with a subordinate anticline near the center which has an axis plunging to the southeast. In the narrow belt extending from sec. 34, T. 65 N., R. 5 W., eastward to the great cross valley in sec. 27, T. 65 N., R. 4 W., the members of the series rest upon the older rocks and uniformly dip to the south. The regularity of this dip is, however, interrupted by a number of minor flexures whose axes plunge south-southeast. As a result, the amount of the dip varies considerably, ranging from about 10° to 65° to the south, the higher dips occurring invariably at the western end of the belt, the dips becoming flatter as the belt is followed to the east. Moreover, these dips vary rapidly within short distances. Likewise the strike, although in general following the trend of the belt, is found to vary gradually within short distances. The uniform dip to the south shows the very simple structure which prevails in this belt, but the changes in angle of dip and in strike clearly indicate the presence of a number of subordinate rolls in these monoclinal southerly dipping series of sediments. The gradual diminution in the angle of dip as the sediments are followed to the east corresponds to the less folded condition of these sediments in this part of the area. Attention has already been called to the areal distribution of the sediments and the westward-trending tongue of sediments occurring in secs. 21 and 22, T. 65 N., R. 4 W., which is good evidence of an infolded syncline of these sediments at this place. The dip of the sediments as observed upon the outcrops in this area gives further proof of the occurrence of this syncline.

In general, then, the sediments have a uniform dip to the south, with minor irregularities, these irregularities being most marked in the western part of the area and in general wherever the sediments lie against the older rocks. Some very considerable irregularities have been noted in a few cases along the margins of certain enormous masses of dolerite which occur in the midst of the sedimentary area. These dolerites, it may be stated here, are intrusive in the sediments, and this fact sufficiently explains the contorted character of the sediments immediately adjacent to them, for this contorted character is confined only to their immediate vicinity, the uniform low southerly dip appearing by the time one has gone some distance from such contact lines.

PETROGRAPHIC CHARACTERS.

The Gunflint iron-bearing rocks at the east end of the Vermilion district correspond stratigraphically to, and are indeed the eastern continuation of, the iron-bearing rocks of the Biwabik formation, which are so well developed and of such enormous economic value in the Mesabi range. Although stratigraphically the same as the Biwabik, the rocks at the eastern end of the Vermilion district, constituting the Gunflint formation, have been in general much more metamorphosed than the Biwabik, and while showing their derivation from rocks similar to those constituting the Biwabik, they are now petrographically very different from them.

The rocks of the Biwabik formation have been described by the Minnesota Geological Survey, especially by N. H. and H. V. Winchell[a] and J. E. Spurr,[b] and a later and more accurate description has been given by Leith.[c] To these articles the reader is referred for details.

The following brief summary made by Leith, while preparing the report on the Mesabi district, describes the petrographic character of the rocks typically developed in that district and may aid in interpreting the petrography of the Gunflint iron-bearing rocks:

The Mesabi iron formation rocks are mainly ferruginous chert, but contain also iron ore, small quantities of iron and calcium carbonates, thin seams of slate and paint rock, and, finally, certain peculiar green rocks containing minute dark-green granules resembling an indurated greensand. The ferruginous chert and the iron ores have been shown to develop mainly from the alteration of the last-named rock. The original green granules under the microscope are seen to lie in a matrix of chert with a variety of textures. They have round, oval, crescent shaped, gourd shaped, or more irregular forms; their color varies from a bright green through a shade of yellowish green to dark brown; under crossed nicols a fine aggregate polarization appears, so fine that the substance appears practically isotropic. The green granules were supposed by Spurr to be true glauconite, but later work by the United States Geological Survey[d] shows the substance to be essentially a hydrated ferrous silicate lacking potash, and quite different in composition from glauconite. Moreover, instead of being entirely organic, as supposed by Spurr, the substance of the green granules is supposed to be the result of chemical developement in a manner analogous to the development of the iron carbonates described by Van Hise for the other districts of the Lake Superior region.[e] The shapes, however, may be due to filling, replacement, or accretion about minute organic bodies, which are probably commensurate in variety both with those depositing glauconite and with those giving the granule

[a] Geol. and Nat. Hist. Survey of Minnesota, Bull. No. 6, 1891, pp. 113–146.

[b] Geol. and Nat. Hist. Survey of Minnesota, Bull. No. 10, 1894, p. 259.

[c] The Mesabi iron-bearing district of Minnesota, by C. K. Leith: Mon. U. S. Geol. Survey Vol. XLIII, 1903, pp. 101–159.

[d] Ibid., p. 108.

[e] Twenty-first Ann. Rept. U. S. Geol. Survey, Pt. III, 1901, pp. 326–328.

shapes to much of the Clinton ore. All stages of the alteration of this green ferrous silicate rock to the ferruginous cherts and iron ores are to be observed. Scarcely a slide of the cherts does not show some traces of the granules. The alterations have been for the most part characteristic of surface conditions and have consisted in the decomposition of the ferrous silicate, the oxidation of the ferrous iron to the hydrated hematite form, and its segregation from the silica. Where metamorphosed by the Keweenawan gabbro the alteration of the granules has consisted in the development of a variety of amphiboles, including actinolite, grünerite, cummingtonite, and perhaps others, of which grünerite is the most abundant, and the partial oxidation of the ferrous iron to the magnetite form.

In the Gunflint formation the rocks very commonly have structural characters indicating their development from ferrous silicate granules in the manner characteristic of the metamorphism by the gabbro—that is, traces of the granular structures still remain; but the characteristic minerals are magnetite and the amphiboles resting in a chert matrix. In addition to the rocks that give a good indication of the kind of rock from which they were produced, there are others that give no such clue. They are without characteristic structural features. We know that ferruginous carbonates form a part of the iron-bearing formation, and it is presumed that some of these metamorphosed products have been derived from such carbonates. It is impossible, however, to give any quantitative estimate of the relative abundance of the ferruginous carbonate and ferrous silicate rocks; so that we can not say which of these has been most important in furnishing material for the rocks of the Gunflint formation.

In general, the least metamorphosed of the Gunflint rocks are thin bedded and consist of bands of nearly pure chert alternating with cherty and granular quartzose bands containing varying percentages of iron carbonate, bands of jasper and magnetitic chert, and others consisting of quartz as a basis with actinolite and grünerite crystals, with which minerals are always associated more or less ferruginous carbonate, magnetite, hematite, and limonite. A description of the least altered Gunflint beds has been given by Irving and Van Hise in their monograph on the Penokee iron-bearing series.[a] The cherty ferruginous carbonates occur in better development just outside of the Vermilion district in Canadian territory, on the north shore of Gunflint Lake, than in the Vermilion district proper. The

[a] Mon. U. S. Geol. Survey Vol. XIX, 1892, pp. 260-268.

following analyses, made by Mr. Thomas M. Chatard, of the United States Geological Survey,[a] give the composition of some of these carbonates.

Analyses of iron-bearing carbonates.

	VII.	VIII.	IX.
Silica	58.23	46.46	23.90
Titanic oxide	Trace.	Trace.	None.
Alumina	.06	.24	.07
Iron sesquioxide	5.01	.64	.44
Iron protoxide	18.41	26.28	10.65
Manganese oxide	.25	.21	.28
Calcium oxide	.38	1.87	22.25
Magnesium oxide	9.59	3.10	8.52
Carbon dioxide	5.22	19.96	32.42
Phosphoric acid	.03	.13	Trace.
Iron sulphide	.14	.11	.13
Water at 110°	.07	.07	....
Water at red heat	2.01	1.15	.99
Total	99.40	100.22	99.65

VII (specimen 10575), iron carbonate from Gunflint beds on eastern side of outlet of Gunflint Lake on international boundary; VIII (specimen 10598), from same beds, but from northern side of Gunflint Lake; IX (specimen 10588), ferriferous carbonate from another part of north side of Gunflint Lake.

Under the microscope most of the above-mentioned rocks show nothing of especial interest. With these one finds cherty ferruginous rocks which, when examined under the microscope, are of interest, since they show the relationship of these rocks to the less altered normal rocks of the iron formation of the Mesabi range, concerning which a brief statement was made a few pages back (p. 378). These rocks consist of rounded areas of fine-grained crystalline silica and limonite and rarely hematite—corresponding exactly in shape to those granules which have been mentioned above—which lie in a groundmass of crystalline silica (see Pl. XII, *A*). These areas are surrounded by a border of limonite, hematite, or these oxides—most commonly limonite—are more or less uniformly distributed throughout the granule or occasionally concentrated at the center. Within the border crystalline silica sometimes predominates, although scattered through it there is more or less limonite, sometimes actinolite and grünerite and a ferruginous carbonate. The iron oxide has frequently a definite arrangement. It has accumulated in aggregates at the centers of fibrous quartz

[a] Mon. U. S. Geol. Survey Vol. XIX, 1892, pp. 191-192.

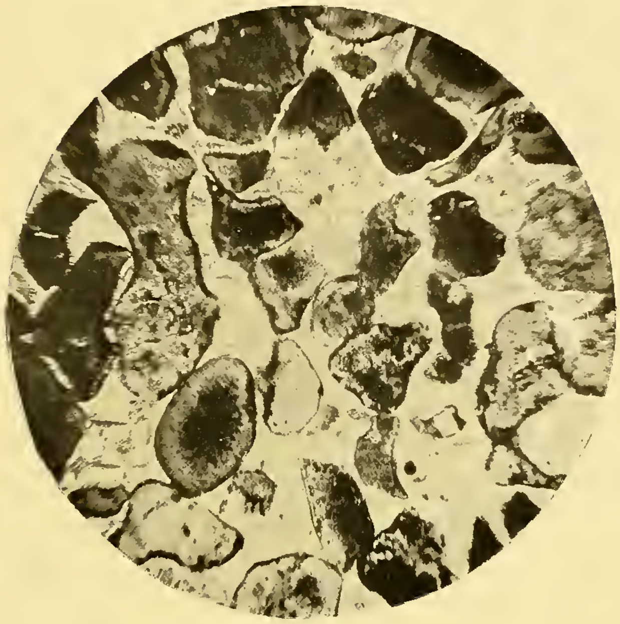
PLATE XII.

381

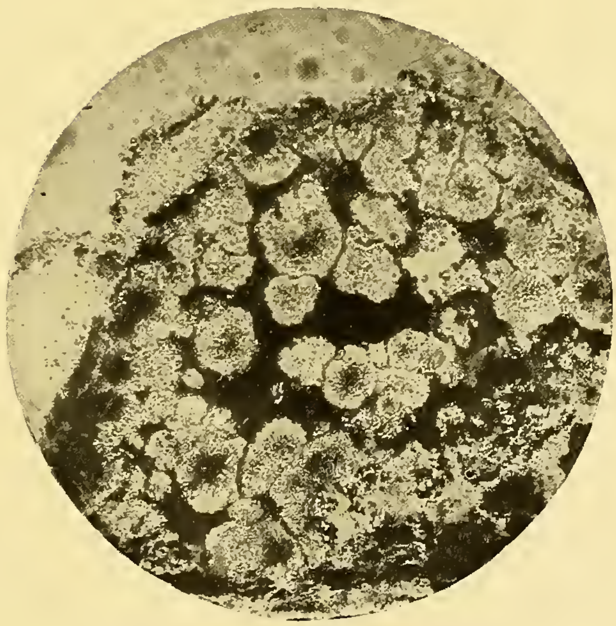
PLATE XII.

A, Photomicrograph showing the granules in the Gunflint formation. These granules, which originally consisted of a green to brownish-green hydrated ferrous silicate, may, after alteration, consist of limonite, hematite, magnetite, ferruginous carbonate, silica, actinolite, and grünerite, in various combinations. Limonite and silica occur very commonly. In this slide the granules consist of hematite and silica. The spherulitic character of the siliceous matrix is well shown by the black crosses. (Slide 29446, 21 diameters, with analyzer, p. 380.)

B, Photomicrograph showing the details in a limonite silica granule. The limonite occurs at the centers and around the peripheries of small spherulitic or granular areas of silica. In the upper right-hand quadrant an area with well-defined agate structure is distinctly shown. (Slide 7004, 80 diameters, without analyzer, p. 383.)



(*A*)



(*B*)

A. PHOTOMICROGRAPH SHOWING GRANULES IN GUNFLINT FORMATION.
B. PHOTOMICROGRAPH SHOWING DETAILS OF GRANULES.

spherulites, and around each one of these spherulites there occurs also a film or thicker layer of limonite, with, in a few cases, some small quantity of hematite. This structure is interpreted to mean that the ferrous silicate originally occupying these areas has been altered into its constituents, iron oxide and silica, the silica forming the radiating areas above mentioned, and the limonite having been retained either at the centers of these areas or forced outward during the processes of crystallization, so as to form a ring now surrounding these areas (see Pl. XII, *B*). That a large part of the silica of the granules is a secondary deposit is shown by the fact that an imperfect agate structure is not uncommon (see Pl. XII, *B*). A similar agate structure also occurs between the large rounded granules referred to Projecting from the sides toward the centers of the spaces between these granules occur also segments of or complete quartz spherulites. This spherulitic structure showing black cross is reproduced in Pl. XII, *A*.

The rocks briefly described above are the least altered forms of the rocks of the iron-bearing formation, and when weathered exhibit on the surface a brown ferruginous crust. As we follow these rocks westward we find that they change somewhat, passing into ferruginous cherts and cherts which have been more or less completely recrystallized into relatively coarse-grained rocks that might be spoken of almost as quartzites—although they are not, as should be clearly understood, metamorphosed clastic sandstones—actinolite, grünerite, and magnetite rocks, in which there is practically no carbonate, or but very little. These rocks, of course, vary greatly in color, ranging from white or gray to brownish, light green, dark green, and practically to black, the color depending on the quantity and kind of the minerals mentioned which are present in them. This is especially true of those rocks that occur in the narrow belt extending from a short distance east of Paulson's mine west nearly to Gobbemichigamma Lake. Here the gabbro is either in immediate contact with or but a short distance from these rocks. The rocks in this area are made up of coarsely crystalline bands of quartz of varying width in alternation with coarsely crystalline bands of magnetite ore, reported to range from 1 inch up to 10 or 12 feet in thickness, and bands of dark-green, brown, or black rocks, which consist of combinations of quartz, augite, hypersthene, hornblende, olivine, and magnetite as the principal minerals, associated occasionally with some ferruginous carbonate, actinolite, and grünerite. These bands, consisting largely of ferromagnesian minerals, vary from medium grain to coarse grain. Occasionally they are characterized by large poikilitic plates of hypersthene several inches in length, which show bright reflecting faces. Most of these rocks when examined under the microscope appear as granular aggregates of the various minerals enumerated and give no clue to the original rock from which they were derived. Some of them, however, still contain the rounded areas to which reference has already been repeatedly made, and show conclusively that they have undergone a more or less complete recrystallization. In these the areas are always outlined by a zone of magnetite, rarely with some hematite. In some cases this magnetite occurs as a very fine dust; in others the magnetite is in relatively large masses. Ordinarily the boundaries between these areas and the adjacent quartz of the groundmass are sharply marked by the magnetite zone. When the areas are close together the magnetite border of the one unites with that of the ones adjacent, and such union tends to destroy the regularity of the areas. Indeed, when the areas are closely crowded they run together more or less. When, in addition to being close together, the interior of the areas is occupied by magnetite, as is commonly the case, the resulting rock is composed of a mass of magnetite with little quartz and none of the rounded granule areas are visible. In many of the areas quartz is the chief constituent, in relatively coarse grains. Within these grains occur dust-like crystals of magnetite which are accumulated either at the centers of the grains or just within their peripheries. Outside of the areas occurs the matrix, which consists now of coarsely crystalline quartz. When viewed between crossed nicols, however, it is seen that the large quartz individuals of which the matrix is composed pass across the boundary and extend into these areas.

We can readily see how such a rock as this might be produced from the one already described (p. 380), in which essentially the same conditions existed, with the difference that the rounded areas of silica and limonite were bounded by limonite, and that the quartz was in fine fibrous spherulitic aggregates with limonite at the centers and bounding their peripheries (Pl. XII, *A*). By dehydration of the limonite there would be produced hematite or, if insufficient oxygen were present, as appears to have been the case throughout this region, magnetite. With the limonitic rocks there is found associated ferruginous carbonate, which also contains undoubtedly some lime and magnesia. Recrystallization of this material in combination with the iron and silica of the adjacent rock might, where the elements were present in proper proportion, very well produce the actinolite, grünerite, and massive hornblende which in some places more or less completely fill out these rounded areas.

The following partial analyses of the iron ores of these Gunflint beds are quoted from Winchell and Grant, and are of interest as showing the practical absence of titanium from them.[a] In this respect they differ very essentially from the titaniferous magnetite ores which form a part of the Duluth gabbro of this vicinity.

Analyses of iron ores of Gunflint beds.

	I.	II.	III.	IV.	V.
Metallic iron, Fe	58.40	54.01	63.98	55.60	62.05
Manganese, Mn	4.92	5.02	None.	4.34	....
Silica, SiO_2	8.22	9.37	8.90	10.02	7.14
Alumina, Al_2O_3	0.52	0.07	....	0.34	....
Phosphorus, P	0.036	0.032	0.028	0.042	0.113
Titanium, Ti	None.	None.	Trace.	None.	....

These iron-bearing rocks were observed by Chauvenet in his reconnoissance through this district in 1884.[b] They were also studied by Bayley[c] and described by him in his articles upon the Duluth gabbro of Minnesota. Chauvenet apparently considered these rocks as a part of the gabbro. W. N. Merriam has also mapped these rocks as part of the gabbro, and Bayley has also described them as a peculiar peripheral phase of the gabbro. H. V. Winchell, of the Minnesota survey, first suggested that they were a phase of the Gunflint formation metamorphosed by the gabbro.[d] This is believed to be the correct explanation of the origin of these peculiar rocks. This explanation was adopted by Spurr and also by Grant, who has described the rocks in

[a] Analyses Nos. I, II, III, and IV, are from Geol. and Nat. Hist. Survey of Minnesota, Bull. No. 6, 1891, p. 138. No. V is from Geology of the Mesabi Iron Range, by U. S. Grant: Engineers' Year Book, University of Minnesota, 1898, pp. 49–62. Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 480.

[b] W. M. Chauvenet, U. S. Geol. Survey, MS. Notes.

[c] The basic massive rocks of the Lake Superior region, by W. S. Bayley: Jour. Geol., Vol. I, 1893, pp. 433–716.

[d] Geol. and Nat. Hist. Survey of Minnesota, Twentieth Ann. Rept., 1893, pp. 120–121, 134–136.

some detail and has brought forward evidence in favor of the hypothesis that they originated by metamorphic action of the gabbro on the Gunflint formation. Grant bases his conclusions as to their mode of origin on the following facts: The magnetite in the Gunflint beds is, as shown by the analyses quoted above, nontitaniferous, whereas that of the gabbro is titaniferous; the large amount of quartz in these beds could not possibly be derived in such quantity from the crystallization of the gabbro magma; feldspar is absent, whereas it is, of course, an essential constituent of the gabbro itself. A further fact, which should be considered as evidence against the view that these iron-bearing beds with the bands of ferromagnesian minerals are a contact or border facies of the gabbro, and as favoring the hypothesis that they are an exomorphic contact product of the gabbro—the explanation which is believed to be the correct one—is the coarseness of the beds in comparison with the recognizable border phases of the gabbro itself. These iron-bearing rocks range from medium- to coarse-grained rocks. In general, they are coarser than the border phase of the gabbro. Such a condition is anomalous. Ordinarily the contact is the finer grained the farther it occurs from the main mass of the igneous rocks. If this were interpreted as a contact phase of the gabbro, here we would have next to the main mass of gabbro a relatively fine- to medium-grained gabbro and then this coarse-grained facies, which in places is made up of bands of coarse-grained pure quartz and the other bands mentioned. The original rocks from which the iron-bearing rocks, and eventually these rocks, were derived, judging from analogy with the correlated iron-bearing formation of the Mesabi district, are supposed to have consisted largely of chert with a hydrous ferrous silicate, that which occurs in the green granules, with which is associated more or less iron, calcium, and magnesium carbonate. From rocks of this composition it is easy to see that the coarse-grained rocks, consisting of quartz, magnetite, olivine, hornblende, augite, and hypersthene, might have been derived by simple recrystallization, without presuming any transfer of material from the gabbro. We know that farther west in the district, where the gabbro lies in contact with the Lower Huronian slates and conglomerates, it has metamorphosed them extremely, producing in them secondary ferromagnesian silicates, hypersthene, hornblende, biotite, and augite, with varying quantities of magnetite. It is not necessary, therefore, to assume any abnormal conditions other than the contact action of the gabbro on beds having the proper composition. Complete recrystallization of properly constituted beds, the process taking place slowly and extending over a long time, would readily account for the existence of these abnormal Gunflint beds. Since we consider this recrystallization of the rocks and production of magnetite, etc., to have taken place as the result of the metamorphism produced by the Duluth gabbro, it is evident that the iron in the rocks must have accumulated prior to Keweenawan time.[a] As the result of the metamorphism the rocks were so changed that no further concentration of iron took place, and consequently we find these deposits in this part of the district differing both in petrographic character and in size from the great deposits of the western Mesabi or Mesabi proper, whose concentration was not seriously interfered with except locally during Keweenawan times, but has continued right on up to the present.

RELATIONS TO OTHER FORMATIONS.

The peculiar Gunflint formation, found at the base of the Upper Huronian, rests upon rocks of different character and of varying age. These range from the granite of Saganaga Lake in secs. 23 and 24, T. 65 N., R. 4 W., through the Ely greenstone to the west of this area, and then up to the Ogishke conglomerate and the Knife Lake slates still farther west. The Duluth gabbro lies against and upon the southern edge of the Gunflint formation.

The Gunflint formation of the Animikie series is found in relationship with the Ely greenstone of Archean age, at one especially well-exposed place in the north side of the cut of the Duluth, Port Arthur and Western Railroad, where it cuts the east end of the high cliff of greenstone on the north shore of Gunflint Lake. Here the iron formation is well banded, and rests, with a very slight dip to the south, on the crinkled green schists derived from the Ely greenstone. At one place about 1 foot of conglomerate was found at the base of this formation. This conglomerate consists of green schist and quartz pebbles, and above this comes a layer of banded white chert about a foot thick in places, and somewhat brecciated. The iron formation proper does not actually appear at the particular

---

[a] Geol. and Nat. Hist. Survey of Minnesota, Bull. No. 10, 1894, pp. 199, 358.

point where the conglomerate was seen, but it does appear a few paces to the east. On the north side of the road, in sec. 30, T. 65 N., R. 4 W., about 500 paces east of Fay Lake, there were found several trenches which cut through the iron formation and showed its contact with the Ely greenstone. Here it seemed to rest upon this greenstone without any intervening conglomerate. Still farther east, at the west end of the Duluth, Port Arthur and Western Railroad, just west of Paulson's camp, the cut has exposed the Ely greenstone with a film of the Gunflint formation lying above it. At this place no well-marked conglomerate exists. The greenstone is more or less broken up and some of the iron formation material has been infiltrated in these cracks, so that on the surface it looks conglomeratic. A glance at the maps in the atlas will show that the area just mentioned, in which the two exposures of greenstone in contact with the Gunflint formation occur, is at the place where the Ely greenstone makes its greatest bend to the south.

Relations to the Lower Huronian series—Ogishke conglomerate and Knife Lake slates.—The Ogishke conglomerate occurs east and west of the southward projecting point of Ely greenstone in sec. 30, T. 65 N., R. 4 W., and sec. 25, T. 65 N., R. 5 W. It is very thin to the east, and in fact its presence has been detected in only one place, as the result of an examination of the dump heaps of the pits northeast of Paulson's mine, in the NW. $\frac{1}{4}$ of sec. 27, T. 65 N., R. 4 W. These pits are just north of the ridge of Gunflint formation, and are in typical bedded rock. This bedded rock occurs in the upper part of the pit, as one can readily see. The lower part of the pit is now filled with water, but some rock on the dump and that forming the top part of the dump, presumably material last taken from the pit, has a distinctly conglomeratic appearance. The matrix is, however, very coarsely crystalline, and the supposed pebbles are well rounded. The kinds of rock which constitute the pebbles could not be determined. This conglomerate certainly resembles very closely, if it is not identical with the Ogishke conglomerate, which occurs farther to the west. There is a bare possibility that it represents a conglomerate at the base of the Gunflint formation belonging with the Upper Huronian series, but, if so, it could not be discriminated from the Ogishke.

West of the southward-projecting greenstone point above mentioned the Ogishke conglomerate appears in typical development. It is first seen along the north side of the road leading to Fay Lake, where it is very thin, but to the west it increases greatly in thickness, until it is found covering an area having a width north and south of nearly a mile along the line between secs. 26 and 27, T 65 N., R. 5 W. The Gunflint formation has been found in direct contact with this conglomerate at a number of places, but in no place could a conglomerate be found which could be said to be at the base of the Gunflint formation and separable from the Ogishke conglomerate. At no place in this district can positive evidence be found of the relation of the Gunflint formation to the underlying Lower Huronian series. Where these rocks are in contact no strike or dip could be found in the conglomerates below the iron-bearing formation. The strike and dip can be determined where the iron formation is separated from the Ogishke conglomerate and Knife Lake slates by an area within which there are no exposures. In these cases the strikes of the rocks are nearly at right angles to each other, and there is a great discrepancy in dip. This evidence weighed in favor of an unconformable relationship. The evidence was not considered conclusive, for in view of the close folding in the district the possibility was recognized that conformable rocks may have been so folded that with lack of exposures showing the actual connection and transition they may appear unconformable.

Indubitable proof of the unconformable relationship of the Gunflint iron-bearing beds to the Lower Huronian series was found by Leith in the Mesabi district.[a]. There the conformable series of rocks—Upper Huronian—to which the Gunflint formation belongs, was found overlying the Lower Huronian series with a basal conglomerate between. Thus the conclusion reached from the study of the imperfectly exposed beds in the Vermilion district was confirmed.

Relations to the Keweenawan (Duluth) gabbro.—In all cases where the Gunflint formation is exposed in the Vermilion district it is found that the Duluth gabbro is in contact with the series on its southern side. It is very noticeable, also, that in all cases where the Gunflint beds are in contact with this gabbro the rocks have been extremely metamorphosed. This metamorphism is most noticeable immediately at the contact, diminishing in extent as the distance away from this contact increases. These facts

[a] The Mesabi iron-bearing district of Minnesota, by C. K. Leith: Mon. U. S. Geol. Survey Vol. XLIII, 1903, p. 180.

afford indisputable proof that the gabbro is younger than the Gunflint formation.

Relations to basic dikes.—The Gunflint beds have been cut by dikes and sills of basalt similar to dikes which cut the Duluth gabbro.

THICKNESS.

The Gunflint formation is shown on the map in the atlas as feathering out in sec. 33, T. 65 N., R. 5 W., near the end of Paul Lake. East of this point it widens very much and reaches its maximum width in secs. 23 and 26, T. 65 N., R. 4 W. East of these sections it again narrows down. Where it is widest the beds have been somewhat crumpled locally by great intrusive sills. Grant[a] has estimated the maximum thickness to be about 825 feet, calculated on an average dip of 10° S., but states that this estimate is possibly too great.

Irving and Van Hise estimated the thickness of the iron-bearing members in the Penokee district of Wisconsin and Michigan to be from 800 to 1,000 feet.[b] This seems to be, however, very close to the true thickness for the Gunflint iron-bearing beds, as shown by comparison with correlative beds in other districts. Thus the Biwabik formation of the Mesabi district, with which this is correlative, has been estimated by Leith[c] to vary from 200 to 2,000 feet in thickness, and to have an average thickness of about 1,000 feet.

SECTION II.—ROVE SLATE.

The sediments constituting this formation lie immediately above the Gunflint formation and have been called the Rove slate from Rove Lake, a lake situated just north of the international boundary and east and outside of the Vermilion district, and lying in a large area underlain by these slates in typical development. Slates occupying the same stratigraphic position and possessing the same general characters occur in the Mesabi district and are there known as the Virginia formation.

---

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 471.

[b] Mon. U. S. Geol. Survey Vol. XIX, 1892, p. 189.

[c] The Mesabi iron-bearing district of Minnesota, by C. K. Leith: Mon. U. S. Geol. Survey Vol. XLIII, 1903, p. 166.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Distribution.—In the Mesabi district south and west of the Vermilion range these slates cover a large area. The Rove slates, which are found in the Vermilion district, represent merely a portion of the slates that cut across the east end of the district and that are not cut out by the Duluth gabbro.

The westernmost exposures of these slates in the Vermilion district are found in sec. 26, T. 65 N., R. 4 W. The formation underlies a very narrow area in the south-central part of the above section, but rapidly widens to the east. The northern boundary of the slates extends northeastward, and is limited by the Gunflint formation and a great dolerite sill. The southern boundary trends east-southeast and the Duluth gabbro everywhere marks their southern extent. At the eastern limit of the map the extreme width of the Rove slate area in the United States is only about 2 miles, and a great deal of this width is taken up by intrusive sills of dolerite, which very materially reduce the areal distribution of the sediments. Beyond the limits of the map the slates have an enormous development in Minnesota and in the adjacent portion of Canada. They may be seen especially well along the Canadian shore of Lake Superior and on the islands in the lake from Pigeon River northeastward to Thunder Cape.

Exposures.—The exposures are usually very good along the lake and wherever steep escarpments occur, which is usually immediately along the lake shores. When the hills stand some distance back of the lakes it is not uncommonly found that although the northern slope is fairly steep, a heavy talus conceals the greater portion of the slates. The slates rarely show any exposures at all, or but very poor ones, on the gentle southern slope of the hills.

Topography.—The topography is that which is usually developed in areas of monoclinal dipping rocks. Ridges have been formed whose trend corresponds approximately to the strike of the slates, here about east and west. These ridges have very steep escarpments on their north faces, where the rocks have been cut directly across the dip, and very gentle slopes to the south which agree in general with the dip. The depressions between the ridges are occupied by lakes, or if not by lakes then by low ground with a stream which eventually flows into a lake. Seen in profile the ridges and intervening low ground present an appearance very similar to that of the teeth of a saw, and from this circumstance they are sometimes called sawtooth mountains. Starting at the north at a lake one ascends a steep ridge rising 200 or 300 feet above the lake in many instances, then descends the gentle dip slope to the south, which leads down to a second depression occupied by a lake, then ascends again a steep northward-facing hill with gentle southerly slope, and so on. Dolerite sills occur intercalated in these Rove slates and usually cap the hills. Their influence on the topography is referred to later on (p. 400). The topographic character of that portion of Minnesota underlain by the Rove formation can be seen in Pl. XIII, *A*, and fig. 21 in the text.

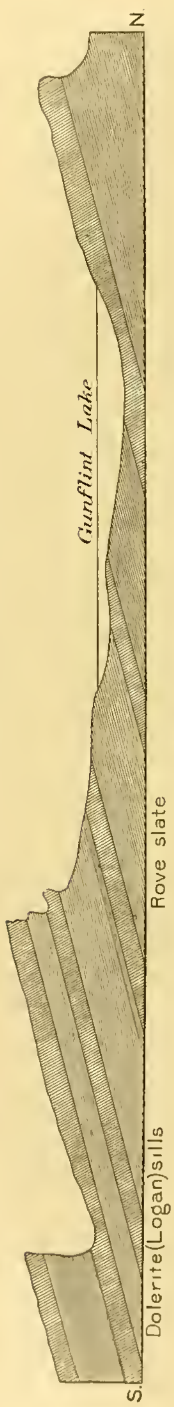


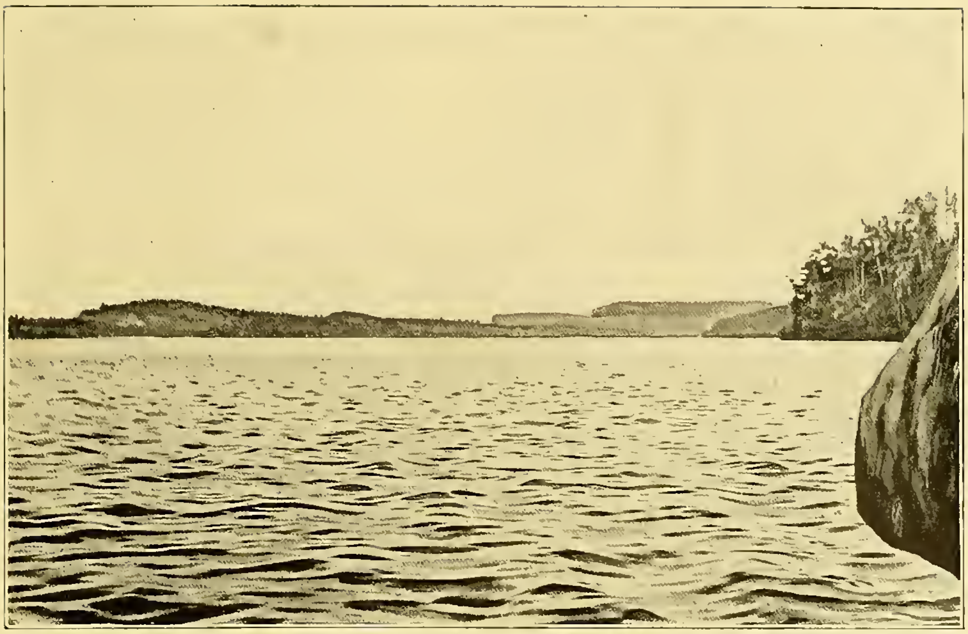
FIG. 21.—Diagrammatic section across the west end of Gunflint Lake, taken from W. M. Chauvenet's manuscript notes, illustrating the characteristic topography of the Rove slate area.

STRUCTURE.

The structure of the slates in this area is very simple. Wherever they have been examined they are found to have a very uniform dip of from 5° to 25° to the south-southeast. They evidently form a part of the great monoclinal series of slates which are known as far west as the Mississippi River in the Mesabi district, and which continue directly east, cross the east end of the Vermilion district, appear on the north shore of Lake Superior north of Grand Portage, and continue thence eastward around Thunder Bay and northeastward along the shore of Lake Superior for some distance. As indicated by the variation in dip—from 5° to 25°—the monocline of slates is occasionally interrupted by minor rolls, which, though of little importance, can be noted by close examination of almost any of the great cliffs that give good exposures.

PETROGRAPHIC CHARACTERS.

The slates form the bulk of the Rove formation, but with them are associated graywackes, some quite slaty, others very massive, and also some fairly pure quartzites.



A. SAWTOOTH HILLS OF ROVE SLATE CAPPED WITH DOLERITE SILLS, AT NORTHEAST END OF ROSE LAKE, INTERNATIONAL BOUNDARY.

B. VIEW ON AN ISLAND IN BURNTSIDE LAKE, SHOWING GRANITE OF BURNTSIDE LAKE CUTTING AMPHIBOLE-SCHISTS—METAMORPHOSED ELY GREENSTONE.

This series of sediments has been divided by Grant,[a] of the Minnesota survey into a "black slate member," with a "graywacke slate member" above it. In our work no attempt has been made to discriminate between these two petrographic facies of the Rove formation. They are not separable by any time interval, but represent merely slight changes in the conditions of deposition. Macroscopically they are very fine-grained black carbonaceous slates, grading up into dark-gray graywackes of medium grain, with occasional bands of material almost sufficiently pure to be called quartzite. In no case were any conglomerates, even fine-grained ones, found associated with these. The slates are unquestionably the predominant kind of rock in the Vermilion district. They are commonly very fissile, although in places these carbonaceous rocks are fairly massive.

Microscopic characters.—The Rove sediments are composed of angular quartz and feldspar grains in a dark cement. In some cases the character of this cement can be partly seen, and one can then recognize shreds of biotite and chlorite. Between these is a very fine-grained dark material which is presumed to consist of minute dust particles of quartz and feldspar and ferruginous and carbonaceous material. Many of these rocks are so well crystallized that they may almost be called phyllites. In these crystalline rocks the material between the grains, probably formed from the decomposition of the fine matrix above referred to, consists of flakes of biotite and chlorite, with quartz and ferruginous matter.

CONTACT METAMORPHISM OF THE ROVE SLATE.

The Rove slate, as has already been stated, is in contact on its southern border with the Duluth gabbro. At numerous places within the formation there are great intrusive sills which are considered to be offshoots from the Duluth gabbro. The reasons for this view will be given in a later chapter. The gabbro and the sills have had a slight contact effect upon the slates adjacent to them. Actual contacts of the sills with the slates in this district were not seen, but a number of contacts of similar sills on similar slates were seen along the Lake Superior shore in the Thunder Bay district of Canada, and in all such cases the slates merely showed a slight induration. Outside of the district, as, for instance, on Pigeon

[a] Geol. and Nat. Hist. Survey of Minnesota, Twenty-second Ann. Rept., 1893, p. 74; Final Rept., Vol. IV, 1899, p. 470.

Point, Minnesota, certain gabbroic intrusives are known to have had a very far-reaching contact effect on these sediments.[a] Along the southern and southeastern shores of Loon Lake were collected several specimens of sediments which were near, although not in actual contact with, the sills. One of these specimens shows a spotted character and is a spilosite such as is fairly common in sediments near the contact with the great mass of gabbro and occurs also in other districts near great dolerite dikes. This spilosite contains a large amount of chlorite in clumps embedded in a matrix of quartz and presumably some feldspar, and forms the microscopic spots. In the Mesabi range some of the slates near the gabbro contact show clearly recognizable cordierite, forming the white spots, and the slates have been metamorphosed to a cordierite-hornstone.[b] In general the slate adjacent to these sills in the Vermilion district shows its normal characters with at most a little metamorphism due to cementation.

A contact of the gabbro with the Rove formation at a point at the southwest end of Loon Lake was examined. This contact is of the gabbro on the "graywacke slate member" of Grant. The sediments at the top of the section were within about 3 feet of the gabbro. This is as near as we found the sediments to the gabbro. Here the rocks are interbanded slates and graywackes which were quite crystalline and hard. Microscopic examination of them shows that the gabbro had effected a partial recrystallization of the sediments and discloses in the sediments a large amount of secondary biotite and muscovite. Both of these occur in relatively large porphyritic plates inclosing grains of the other materials constituting the slate, recognizable quartz, and ferruginous material. As the rocks are studied, as we go down the slope, they are seen to be less indurated, until near the bottom of the section at the water's edge, about 50 feet below the gabbro, the sediments do not appear essentially different from the ordinary rocks of this character and of this age. It is clear from this that the effect of the gabbro has not been felt at a very great distance from the actual plane of contact with the sediments.

---

[a] On some peculiarly spotted rocks from Pigeon Point, Minnesota, by W. S. Bayley: Am. Jour. Sci., 3d series, Vol. XXXV, 1888, pp. 388–393. Abstract, Nature, Vol. XXXVII, 1888, p. 91 (5 lines). Rocks on Pigeon Point, Minnesota, and their contact phenomena: Bull. U. S. Geol. Survey No. 109, 1893, pp. 121.

[b] The Mesabi iron-bearing district of Minnesota, by C. K. Leith: Mon. U. S. Geol. Survey Vol. XLIII, 1903, pp. 171–172.

RELATIONS TO ADJACENT FORMATIONS.

The relations of the Rove slates to the other formations of the district are easily determined. The oldest rock with which they are in contact is that which has been described as the Gunflint formation. The slates are a conformable series of sediments overlying this formation, and consequently younger than it. In previous pages the relations of the Gunflint formation to the other older rocks of the district have been described, and it is not necessary to add anything to the statement concerning the age of the Rove slates other than that they are younger than all of the rocks below the Gunflint formation.

Relations to Keweenawan dolerite.—In places the Rove slates are found in contact with great masses of dolerite. Near the contact the sediments are found to be harder than elsewhere, and in some places to have had produced in them minerals which are evidently of secondary origin, corresponding to the products of contact metamorphism, which have been studied in other districts. This induration is undoubtedly due to the metamorphic action of the dolerite. This alone is proof of the fact that the dolerite is younger than the sediments. In addition to this proof, however, we have the further evidence of the contortion of the slates, which has been noticed in a number of places where the beds were in contact with the dolerites, having been intruded by them. Moreover, the dolerites themselves are much finer grained at the edge than elsewhere. These three facts—the fine-grained character of the edges of the dolerite masses, the induration of the slates along this contact, and the contortion of the beds—form indubitable evidence that the dolerites are younger than and intrusive in the slates.

Relations to Keweenawan (Duluth) gabbro.—The only place where a good contact between the gabbro and the slates was observed is that mentioned above, on the southwest side of Loon Lake. Here the gabbro overlies the slates, and produced considerable changes as the result of its contact with them. The superposition of the gabbro and the contact zone in the slates afford conclusive proof of the relative ages of the two, the Duluth gabbro being very clearly younger than the Rove slate.

AGE.

From the foregoing statements we see that the Rove slates and graywackes form the youngest member of the Animikie series in the Vermilion district. The only rocks younger than it are the dolerite sills, the Duluth gabbro, and the occasional basic and acid dikes which cut through the gabbro.

THICKNESS.

Only a very small portion of the sediments which constitute the Rove slates in the Lake Superior region are represented in the Vermilion district. As has been shown by the distribution, only the apex of a V which rapidly widens to the east is there present. The gabbro of Keweenawan age comes in from the south and swings up northwestward, cutting across the east-west striking slates, and producing the V above referred to. In the Vermilion district, then, the Rove slates vary from a minimum, at the point of the V, up to a maximum for that district which attains a considerable thickness. No attempt to measure the maximum thickness for this district has, however, been made, as it would give merely the thickness of a portion of the slate formation, and not that of the formation as a whole. The latest estimate for that part of the slates present in the Vermilion district is that made by the Geological and Natural History Survey of Minnesota. According to this, the "Graywacke Slate Member" has a thickness of 1,650 feet, the "Black Slate Member" a thickness of 950 feet, and the sills intruded in these rocks a thickness of about 250 feet. This gives a total thickness for the sediments of the Rove formation exposed in this district of 2,600 feet. No statement is made as to the section on which the estimate of this thickness was based, but it was presumably between Gunflint and North and South lakes, just east of the limits of the area shown on the accompanying map of the Vermilion district, Pl. II. The formation has been studied at various places by a number of geologists, and varying estimates have been made of its total thickness. According to estimates made by Irving,[a] the Animikie series of slates corresponding to the Rove slates of the report has a thickness of 10,000 feet. Ingall has estimated this thickness at 12,000 feet.[b]

In 1892 Irving and Van Hise[c] gave an estimate of 11,000 feet as the maximum thickness of the Animikie slates in the Penokee district.

[a] Mon. U. S. Geol. Survey Vol. V, 1883, p. 380.
[b] Geol. and Nat. Hist. Survey of Canada, Ann. Rept. for 1888, II, p. 26.
[c] Mon. U. S. Geol. Survey Vol. XIX, 1892, p. 299.

CHAPTER VI.

THE KEWEENAWAN.

INTRODUCTION.

The only rocks of Keweenawan age in the Vermilion district are gabbros which form a part of the Duluth gabbro mass of northeastern Minnesota, certain great basic sills to which the name Logan sills has been given, and some few basic and acid dikes which cut all of the rocks of the district, including the aforementioned gabbros and Logan sills. As a result of the studies reported in this monograph, it has been determined that stratigraphically the Duluth gabbro and the Logan sills belong together, although they show slight differences in lithologic character. These differences are due essentially to variations in the conditions of consolidation. Since these two rocks belong together, they will be described under the same section in the following pages. A second section will be devoted to a brief mention of the basic and acid dikes, which are the youngest rocks of the Vermilion district, excluding always the Pleistocene glacial-drift deposits.

SECTION I.—DULUTH GABBRO AND LOGAN SILLS.

References to the great gabbro mass of northeastern Minnesota are common in the geologic literature of the Lake Superior region. The name Duluth is given to this gabbro since it is so well developed near the city of that name. This rock is conspicuously developed on the north shore of Lake Superior, where it forms a prominent part of the Keweenawan series of northeastern Minnesota, underlying several hundreds of square miles. It is also well known upon the south shore in the Keweenawan district of Wisconsin.

North of the Duluth gabbro, and extending all around the north shore of Lake Superior as far as the Slate Islands of the northeast shore of the lake, it has been found by the various geologists who have worked in this territory, beginning with Logan,[a] that the sedimentary rocks of this region, slates, quartzites, and graywackes, have intercalated in them at various horizons sheets of basic igneous rock ranging in thickness from 1 to 100 feet. These vary in character from distinctly gabbroic rocks in the centers of the large masses through all gradations of finer-grained granular and porphyritic rocks to the very fine-grained basaltic phases which form the thin sheets and occur as well-formed selvages of many of the thicker sheets. These are the intrusive sheets which have been called the Logan sills by Lawson,[b] in recognition of the geological work done by that pioneer of investigation in this field.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Distribution.—The Duluth gabbro forms the southern boundary of the pre-Keweenawan rocks throughout the greater portion of the Vermilion district. The westernmost point at which the Duluth gabbro touches the district is in secs. 26 and 35, T. 63 N., R. 10 W., and section 3, T. 62 N., R. 10 W. From these sections on along the Kawishiwi River the Duluth gabbro swings off to the northeast with a broad sweep, extending just within the area mapped as far east as the vicinity of Paulson's mine, in sec. 28, T. 65 N., R. 4 W. From this place its edge trends to the southeast, passing beyond the limits of the area mapped toward Lake Superior. A couple of small isolated outliers have been found north of Gobbemichigamma Lake. The southernmost one is only a quarter of a mile from the northern edge of the main mass of the gabbro, northwest of Paulson Lake, and the other is about three-fourths of a mile from the nearest point on the edge of the gabbro and lies in the NW. $\frac{1}{4}$ sec. 29, and NE. $\frac{1}{4}$ sec. 30, T. 65 N., R. 5 W.

The sills lie well within the district to the north of the edge of the gabbro mass, varying in distance from this edge. The first exposure of such a sill was noticed on the southwest side of Gobbemichigamma Lake, but this can not be traced far. The next one was seen near Bingoshick Lake. This sill has been followed to the east for several miles to a point east of Paulson's mine, having throughout this distance an almost continuous outcrop. Parallel to this sill several small and relatively unimportant sills have been

[a] Geological Survey of Canada, 1846–47, p. 13.

[b] The lacolitic sills of the northwest coast of Lake Superior, by A. C. Lawson: Geol. and Nat. Hist. Survey of Minnesota, Bull. No. 8, pt. 2, 1893, pp. 48.

observed. Beyond Paulson's mine the Upper Huronian sediments begin to widen, rapidly increasing in width as they are followed to the east, as already described. Corresponding with this widening, we find an increasing number of sills having in general a trend east and west and lying approximately parallel to each other. During several trips to Gunflint Lake and to the country to the south a number of these sills were followed along their strike for short distances and were also crossed at right angles to the strike. Their relations to the sediments were thus clearly seen. No attempt was made to trace out the individual sills. This work has been done in previous years by Chauvenet[a] and Merriam,[b] of the United States Geological Survey, and in more recent years by U. S. Grant,[c] of the Minnesota Survey.

The data for the distribution of the sills which are shown on the accompanying map have been taken chiefly from the reports of these men.

Exposures.—Throughout the area underlain by the gabbro, as well as the sills, exposures are very numerous and usually of large size, affording excellent opportunities for the study of the characters of these rocks, their variations in grain, and also their relations to the adjacent sediments.

Topography.—The line of contact between the gabbro and the older rocks adjacent to it is fairly well marked by a slight topographic break. The gabbro normally has a steep north face sometimes showing an escarpment of varying height. It is never very high, but is considerably higher than any topographic features in the area north of it for some distance. The contact is frequently marked by a lake or a stream. This difference between the topography of the gabbro area and that to the north exists at the immediate contact, but examining contrasting areas as a whole we find that in general the gabbro area is lower than that underlain by the older formations to the north. Locally the gabbro area has been reduced almost to base level. In fact, this area may be described as very nearly a plain, but one with minor but pronounced irregularities. The uniformity of the surface is due in great part to the homogeneous character of the gabbro mass, which has caused it to be about equally affected by the various agents which have attacked it. The minor pronounced irregularities are usually found to be due to erosion, which has been controlled very frequently by the joints of the gabbro, and

---

[a] W. M. Chauvenet, U. S. Geol. Survey, manuscript notes.
[b] Mon. U. S. Geol. Survey Vol. XIX, 1892, Pl. XXXVII.
[c] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, pp. 487–488.

to differences in composition where such exist. For example, the anorthosite masses usually stand out conspicuously from the surrounding more basic and less resistant portions of the gabbro.

The lakes of the gabbro area are, as a rule, shallow, and they are also very irregular, and can not be said to possess uniformity of long extension in any one direction, as is so markedly the case in the lakes of the other

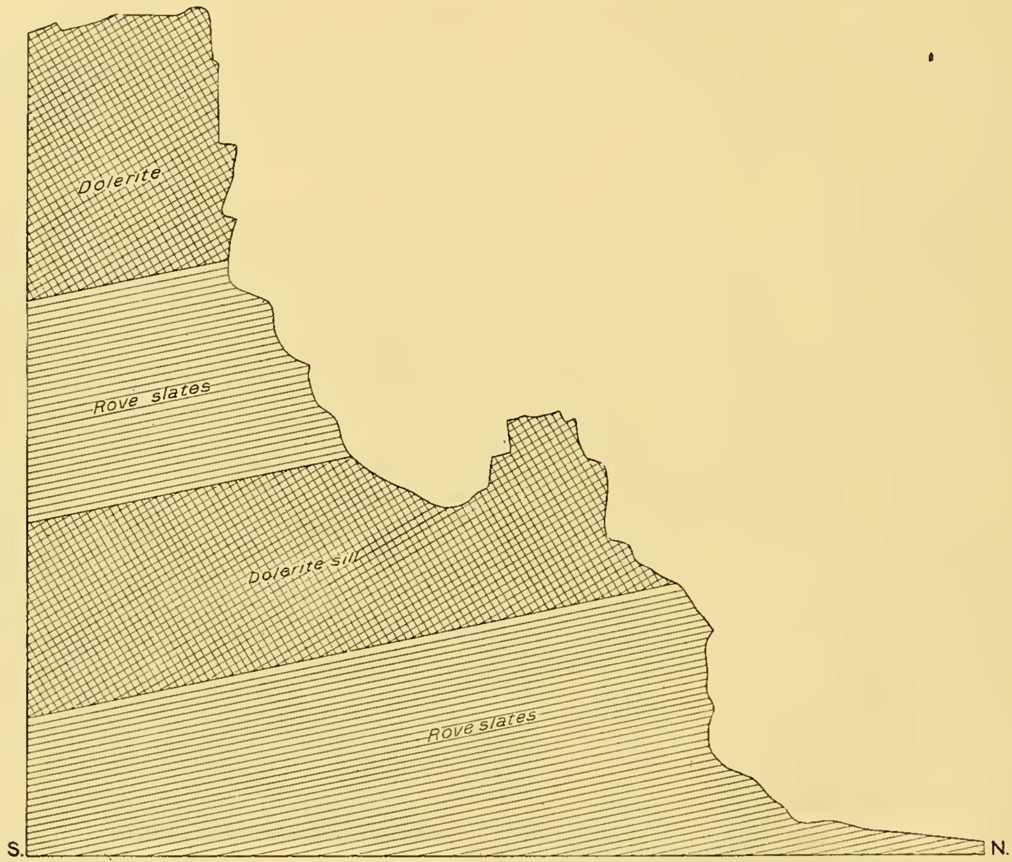


FIG. 22.—Section through the Rove slates, with intercalated Logan sills south of Gunflint Lake.

portions of the Vermilion district. On the contrary, they spread out in all directions, sending off numerous bays, some of which are very long and narrow, and all very irregular in shape.

The Logan sills exercise a very material influence upon the topography of that portion of the district north of the gabbro in which they occur. It will be recalled that the Upper Huronian (Animikie) sediments in this vicinity have a monoclinal dip to the south. The sills have been injected essentially parallel to the bedding of the sediments, although occasionally they are found cutting across the beds at low angles. Erosion has been most active in this portion of the district in a direction parallel to the strike of the beds, and consequently most of the large valleys trend in agreement with these, approximately east and west. The resistant sills now form the caps of the ridges, the slates having been removed down to the sills. The massive rock forming the sills breaks off along the joint planes, and this breaking results in forming perpendicular cliffs, below the foot of which talus from the sills and from the easily weathering Rove slates give a gentle slope. These sills are sometimes very nearly concealed by the accumulated talus derived from them.

The effects of erosion have produced a series of hills with very nearly vertical north escarpments, and a gentle slope from the crest of the hills to the south. This slope corresponds very closely to the dips of the Rove slates and the upper surface of the dolerite sills. Fig. 22 shows a somewhat idealized section through the ridge on the south side of Gunflint Lake, taken from W. M. Chauvenet's manuscript notes.

PETROGRAPHIC CHARACTERS OF THE GABBRO.

Macroscopic characters.—It is not the purpose of this report to consider in detail other rocks than those of pre-Keweenawan age which make up the Vermilion district in its strict sense. In order, however, to give a complete description of the area shown on the maps in the accompanying atlas, it is essential to consider at least briefly the Duluth gabbro. Specimens have been taken here and there along its margin, and several trips have been made well down into the gabbro, during which specimens were collected of the varieties seen and observations made on their relations. The following brief description of the gabbro is the result chiefly of the study of these specimens. No attempt has been made to obtain specimens from all parts of the gabbro, and consequently numerous facies which would be seen only after very detailed studies of the gabbro have, of course, not been found. For more detailed descriptions of this gabbro the reader is referred to the reports of the Minnesota survey, especially to the articles by Elftman[a], Grant,[b] and Winchell,[c] and to the petrographic study of the gabbro

[a] Am. Geologist, Vol. XXII, 1898, pp. 131–149.

[b] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 476 et seq.; Twenty-third Ann. Rept., 1894, pp. 224–230.

[c] Am. Geologist, Vol. XXVI, 1900, pp. 151–188, 197–245, 261–306, 348–388.

by Bayley.[a] The gabbro, as a rule, was found to be a medium- to coarse-grained rock, with essentially the same granular texture throughout. However, near the contact of the gabbro with the other rocks to the north of it, it is found to grow much finer grained. This gradation is rapid. Thus the gradation from a medium fine-grained to a normal coarse-grained rock was completed within a distance of about 10 paces. Occasionally large areas of the fine-grained phase of rock which has been called granulitic gabbro occur in the midst of the main gabbro mass. This fine-grained material is found to have very sharp contacts[b] with the coarser-grained gabbro, and small areas of this fine-grained material are also included in rounded as well as irregular masses within a coarse-grained gabbro, possibly indicating that there is a slight difference in age between the two. This fine-grained gabbro at the point referred to has a remarkable horizontal jointing, as the result of which it looks at a short distance like a bedded rock in layers of from 2 to 6 inches thick. It also has a sheeted structure striking in a general way east and west and dipping to the south. This structure is brought out by the differential weathering. In some cases also the gabbro has a very distinctly banded structure, as has been described by Grant.[c] He describes an exposure near south end of Bald Eagle Lake as having a gneissic structure which is practically vertical and runs N. 15° W., making the rock break more readily in this direction than in any other. "In some places the gabbro lies in horizontal beds from 2 to 4 inches thick. The rock seems to be almost entirely composed of a feldspar (probably labradorite) and a mineral which is probably olivine; this, when not decayed, is of a yellowish green color." Microscopic studies show this mineral to be olivine. This occurrence is very similar to the banded faces of the gabbro which may be seen upon the St. Paul and Duluth Railroad between Short Line Park and Smithville, and also upon the shore of Lake Superior between Split Rock Bay and Beaver Bay.

A number of varieties of the gabbro were seen upon Little Saganaga Lake. The gabbro varies from the very coarse-grained varieties to forms

[a] The basic massive rocks of Lake Superior, by W. S. Bayley: Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. I, 1884, pp. 688–716; Vol. II, 1888, pp. 819–825; Vol. III, 1895, pp. 1–20.

[b] Grant, U. S. Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 447, Pl. MM, figs. 5 and 6, and p. 489, fig. 89.

[c] Geol. and Nat. Hist. Survey of Minnesota, Seventeenth Ann. Rept., 1888, p. 164.

which have rather a fine grain, these two grading into each other. In places the gabbro becomes so feldspathic that it can be correctly spoken of as anorthosite. These anorthosite masses usually weather white, and being more resistant than the more basic gabbro stand out as bare, white, conspicuous knobs. In examining these anorthosite masses, which are beautifully exposed in numerous places on the islands and west and southwest shores of this lake, one finds scattered through them irregular and roundish areas of what appears to be normal gabbro. This grades directly into the anorthosite. Furthermore there are also seen finer-grained facies of the gabbro in small, rounded areas occurring in the midst of the anorthosite and grading into the surrounding anorthosite. It thus appears that the anorthosite grades both into the normal gabbro of coarse grain and also into the normal gabbro of fine grain, thus showing both a mineralogic and textural gradation. The more basic areas which are scattered through the anorthosite range in size from 1½ inches in diameter to 4 or 5 inches in diameter. Between these basic masses lies the anorthosite, which makes up the greater portion of the rock, covering much larger areas than are occupied by the basic parts. The basic portions weather more readily than the anorthosite, producing a pitted surface upon the exposures. When disintegration proceeds much farther, the anorthosite is apt to break down into rounded bowlder-like masses.

In many places, and especially near the northern contact, the gabbro is found to be very friable, and this character seems to be due to a considerable extent to some character of the rock dependent upon its contact with the adjacent formations, for specimens taken farther within the mass were uniformly fresher and harder.

The exposures normally show a rock of dark color, either dark-reddish brown, or black, varying, as is stated above, to the anorthosite, which is of rather rare occurrence, and has a gray to white color. The other extreme in the variation from the anorthosite is represented by masses consisting essentially of titaniferous magnetite, such as is well developed at Mayhew Lake[a] and especially at Iron Lake.[b]

The chief components, plagioclase, feldspar, pyroxene, olivine, titaniferous magnetite, are clearly recognized in hand specimens. With these

[a] W. M. Chauvenet, U. S. Geol. Survey, manuscript notes.
[b] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 489.

are found occasionally as accessory minerals, hypersthene, biotite, and hornblende.

Microscopic characters.—The gabbros were referred to above as being generally distinctly granular rocks. In addition to the granular texture one can recognize under the microscope the poikilitic and ophitic textures. The poikilitic is the most common, and in rocks possessing this texture we find plates of hornblende, augite less commonly, and biotite very rarely, the poikilitic minerals including individuals of other minerals. The ophitic texture occurs in the coarse gabbros, but is more common in the finer-grained forms. The presence of this ophitic texture in these rocks is interesting as showing the gradations in textures from the very coarse gabbros to the finer-grained dolerites. The following are the original constitutents which are still present in the gabbro: Augite, hypersthene, olivine, a little brownish-green hornblende, biotite, apatite, and magnetite. The plagioclase has been determined by Bayley[a] to be near basic labradorite in character. These minerals do not possess any very exceptional characters. Moreover, they have been described in great detail by Bayley[b] in his articles on the Duluth gabbro mass of northeastern Minnesota. The only secondary mineral that has been observed is the serpentine. The rocks are normally very fresh indeed. They vary considerably in mineralogic composition. In some cases the feldspar is practically the only mineral present, associated with only occasional grains of magnetite, and rounded individuals of augite, forming anorthosite. With the feldspar occurs occasionally a large amount of olivine and some titaniferous magnetite. From the anorthosite phase the rock grades through facies containing the ferromagnesian minerals in increasing quantity to the nearly pure titaniferous magnetite ores as the extreme variation. Occasionally the rock consists of nearly pure augite with very little feldspar. Sometimes the biotite is present in considerable quantity, producing the biotite-gabbro. These are the varieties which we have observed. Many details concerning these gabbros are given by Bayley[c] in the papers already referred to. The chemical composition of the gabbro is also here given. These analyses

[a] The basic massive rocks of the Lake Superior region, by W. S. Bayley: Jour. Geol., Vol. I, 1893, p. 700.

[b] The basic massive rocks of the Lake Superior region, by W. S. Bayley: Jour. Geol., Vol. I, 1893, pp. 433–716; Vol. II, 1894, pp. 814–825; Vol. III, 1895, pp. 1–20.

[c] Loc. cit., p. 712.

were made for Dr. Bayley in the Survey laboratory, and were reported by him in the papers above referred to.

No. 8589 contains a large proportion of diallage and olivine, while No. 8786 is more nearly of the average composition of the entire mass.

Analyses of Duluth gabbro.

Constituent.	8589.	8786.
SiO_2	45.66	46.45
TiO_2	.92	1.19
P_2O_5	.05	.02
Al_2O_3	16.44	21.30
Cr_2O_3	Tr.	....
FeO	13.90	9.57
Fe_2O_3	.66	.81
NiO	.16	.04
MnO	Tr.	Tr.
CaO	7.23	9.83
MgO	11.57	7.90
K_2O	.41	.34
Na_2O	2.13	2.14
H_2O at 105°	.07	.14
H_2O above 105°	.83	1.02
Total	100.03	100.75

PETROGRAPHIC CHARACTERS OF THE LOGAN SILLS.

Macroscopic characters.—The rocks forming the Logan sills are normally black, medium- to coarse-grained rocks, although varying to fine-grained aphanitic facies upon the edges of the sills. Occasionally the rock is a porphyry, with the feldspars as the phenocrysts. Some of the phenocrysts reach 4 inches in length, but they are normally smaller, ranging from 1 inch to 2 inches. Very frequently we find these feldspars collected into large masses which are made up almost entirely of these minerals. Such areas usually possess as the result of weathering a light gray or almost white color. The relatively slightly altered masses resemble very closely in appearance the anorthosite of the Duluth gabbro mass. As will be seen from the description given below, the sills are formed of rocks which have the composition and characters possessed by the modern dolerites, and they are here called dolerites.

Microscopic characters.—In exceptional cases in the very coarse-grained rocks the texture is almost granular. More commonly we find an ophitic texture imperfectly developed, with the feldspar occurring in very irregularly bounded but in general lath-shaped forms, and the augite in more rounded grain-like forms than is common. The normal ophitic texture is very commonly developed in these rocks, and this grades over into the intersertal texture which is especially well developed in the fine-grained border facies. The fact should be emphasized that while the ophitic texture is the one which is most commonly developed in these rocks, there is occasionally observed an imperfectly ophitic texture grading into a more or less granular texture, and this will be referred to later as evidence in favor of the close relationship of the rocks of these sills with the gabbro.

Constituents.—The rocks are very fresh, and the constituents of them are, in order of prominence, augite, feldspar, titaniferous magnetite, then brownish-green hornblende, and some brown biotite. The biotite is occasionally present in sufficient quantity to warrant our speaking of the rocks as mica-dolerites. The only secondary mineral observed is a light-green amphibole derived from the uralitization of the augite. The rocks are normal dolerites, as shown both by their mineralogic composition and textures.

RELATIONS OF THE GABBRO TO ADJACENT FORMATIONS.

Within this district the gabbro lies adjacent to the following formations, given in order of age from below up:

The Ely greenstone (Archean).

Lower Huronian sediments: Ogishke conglomerate and Knife Lake slates.

Giants Range, Snowbank, and Cacaquabic granites.

Upper Huronian sediments: Gunflint and Rove formations.

Relations to the Ely greenstone.—The gabbro cuts across the greenstone anticline which occurs to the east of Disappointment Lake, and is also in close proximity to but not in absolute contact with the greenstone of the Twin Peaks anticline on the southwest side of Gobbemichigamma Lake. In both of these cases the greenstone has been metamorphosed by the gabbro, showing conclusively the relative epoch of formation of the two rocks.

Relations to Lower Huronian sediments.—At a number of places which may be seen by reference to the maps in the atlas (Pls. XV, XVI) the gabbro is in contact with the Lower Huronian sediments, and in all cases where the contacts have been studied the sediments have been found to have been extremely altered as the result of their proximity to the gabbro. Minerals have been produced in these sediments which are in some cases closely related to, in others identical with, the minerals occurring in the gabbro itself. The quantity of these minerals increases as the gabbro is neared, and all evidence points unquestionably to the intrusion and metamorphism of the sediments by the younger gabbro.

Relations to Giants Range granite.—The Giants Range granite and the gabbro occur together in the vicinity of the Kawishiwi River, and their relations are disclosed by a dike of gabbro, which is found cutting this granite just to the south of the falls in sec. 19, T. 64 N., R. 9 W., showing that the gabbro is younger than the granite.

Relations to Snowbank and Cacaquabic granites.—No contacts have been found between the Snowbank granite and the gabbro, or between the Cacaquabic granite and the gabbro. Since both of these granites are older than the Upper Huronian sediments, which we know have been intruded by the gabbro, the conclusion is evident that they must be older than the gabbro.

Relations to Upper Huronian sediments.—The gabbro is in contact, at a number of places, with the Upper Huronian sediments, both the Gunflint formation and the Rove slates. In all cases, metamorphism, which the gabbro has produced upon these sediments as the result of its contact, offers conclusive evidence that it is younger than they are.

Relations to the Keweenawan.—Irving has placed this gabbro in the Keweenawan chiefly as the result of his studies of it in Wisconsin,[a] and his later work sustained him in his views, as is shown by the fact that after his studies in Minnesota[b] he still retained it in its same stratigraphic position. This is not the place for a detailed historical review of the various opinions which have been held as to the stratigraphic position of the gabbro. Reference to the annual reports of the Minnesota survey will show that the opinions entertained by the members of that survey as to its

[a] Geology of Wisconsin, Vol. IV, p. 171.

[b] The copper-bearing rocks of Lake Superior by R. D. Irving: Third Ann. Rept. U. S. Geol. Survey, 1883, pp. 93–180. Mon. U. S. Geol. Survey Vol. V.

relations to other rocks have varied greatly, although in the Final Report (Vol. IV) it is regarded as of Keweenawan age, in general agreement with the results obtained by others who have worked upon this problem. Winchell[a] makes it the igneous base of the Keweenawan.

As the result of work done during the field season of 1900 fairly conclusive proof has been obtained of the fact that the gabbro is in reality intrusive in the volcanic Keweenawan, and consequently younger at least than a portion of the Keweenawan. This intrusive relation was observed just west of the west end of Brulé Lake. Brulé Lake lies within a syncline of Keweenawan lavas, bounded on the south and west by the Duluth gabbro and on the north by the "red rock" of the Minnesota survey. From this great gabbro mass at the west end of the lake an eastward-projecting tongue of gabbro was traced into the volcanics. This tongue near the gabbro possessed the normal characters of the main gabbro mass, but to the east it narrowed rapidly and its lithologic characters changed until where narrowest, just before it disappeared in a topographic depression, it had graded into a porphyritic rock of comparatively fine grain, with a selvage which was very nearly basaltic. The lavas were upon both sides of this tongue. The actual contact between the gabbro and the lava was not found, but they were separated at one place by an interval of only about 1 foot, and this was the place where the tongue showed its finest grain. The connection of this tongue with the gabbro and the variation in grain in the tongue seem to be very good evidence of the intrusive character of the gabbro.

RELATIONS OF THE LOGAN SILLS TO ADJACENT FORMATIONS.

Relations to the Upper Huronian (Animikie).—Up to the time of the publication in 1893 of Lawson's[b] paper on the laccolitic sills of the northwest coast of Lake Superior, all of the earlier writers on the Lake Superior region, with the exception of Irving[c] and Ingall[d] had held the sheets of basic rock which they observed intercalated between the Huronian slates to be of volcanic origin—that is, surface flows interbedded with the

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 298.

[b] The laccolitic sills of the northwest coast of Lake Superior, by A. C. Lawson: Geol. and Nat. Hist. Survey of Minnesota, Bull. No. 8, pt. 2, 1893, pp. 24–48 See this for references to writers giving details of sills which can not be given in present paper.

[c] Mon. U. S. Geol. Survey Vol. V, 1883, p. 379.

[d] Geol. and Nat. Hist. Survey Canada, Ann. Rept., 1888, II, p. 25.

sediments. Ingalls held that some of these masses were of intrusive origin. Irving considered them all as intrusive.

Chauvenet, in his manuscript notes, refers to a dike which he places with the Logan sills, cutting the Animikie slates on Pigeon River. This rock is clearly an intrusive dike in the slates. The edges of the slates next to the dike are much shattered and broken, as the result of this intrusion.

In the Minnesota[a] reports these sills are referred to as intrusions in the Animikie slates, but are included in the description of the Animikie which corresponds to our Upper Huronian Series.

Lawson[b] asserts that these sills are all intrusive, and fortifies his statement by proof which seems to be unquestionable, as the following quotations of the summary of his argument from his paper will show:

I. The trap sheets associated with the Animikie strata are not volcanic flows, because of the combination of the following facts:

1. They are simple geological units, not a series of overlapping sheets.

2. They are flat with uniform thickness over areas more than 100 square miles in extent, and, where inclined, the dip is due essentially to faulting and tilting.

3. There are no pyroclastic rocks associated with them.

4. They are never glassy.

5. They are never amygdaloidal.

6. They exhibit no flow structure.

7. They have no ropy or wrinkled surface.

8. They have no lava-breccia associated with them.

9. They came in contact with the slates after the latter were hard and brittle, and had acquired their cleavage; yet they never repose upon a surface which has been exposed to subaërial weathering.

II. They are intrusive sills, because of the combination of the following facts:

1. They are strictly analogous to the great dikes of the region: (*a*) In their general relations to the adjacent rocks, and in their field aspect; (*b*) in that both the upper and lower sides of the sheets have the facies of a dense aphanitic rock, which grades toward the middle into a coarsely crystalline rock.

2. They have a practically uniform thickness over large areas.

3. The columnar structure extends from lower surface to upper surface, as it does from wall to wall in the dikes.

4. They intersected the strata above and below them after the latter had been hard and brittle.

5. They may be observed in direct continuity with dikes.

6. They pass from one horizon to another.

---

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, pp. 476; 487–488.

[b] Lawson, loc. cit., p. 29.

8[7]. The bottom of the sedimentary strata above them, wherever it is observable, is a freshly ruptured surface.

9[8]. Apophyses of the trap pass from the main sheet into the cracks of the slate above and below.

10[9]. The trap sheets, particularly at the upper contact, hold included fragments of the overlying slates.

11[10]. They locally alter the slates above and below them.[a]

The writer does not believe that the faulting suggested in I, 2, above, explains the structure of the rocks, as no evidence in favor of this faulting has been observed. Facts have been observed in the Lake Superior region which are corroborative of Lawson's other statements in all their essentials, and confirm his conclusions.

Relations of sills to Keweenawan.—Lawson[b] goes still further, and draws the important conclusion from evidence observed during his field work that these sills are not only later than the Animikie sediments, but are intrusive in the Keweenawan, and states it as his opinion that they are identical in age with many of the heavy sheets of dark diabase or gabbro which prevail on the Minnesota coast, particularly in the eastern portion. He therefore places the sills as post-Keweenawan, and possibly of Silurian age. The writer dissents altogether from the idea that these sills and dikes can be post-Keweenawan, since nowhere in the Lake Superior region have the Cambrian rocks been found to be cut by dolerite sills and dikes, or indeed by any intrusives. While the sills may be younger than part of the Keweenawan, there is no reason for supposing them younger than all of the Keweenawan, but they may belong to the same period of igneous activity and be merely one of the later expressions of this activity, when the molten magma was too deeply buried to reach the surface freely as flows, and was intruded between the sediments of the Animikie and the lava sheets of the Keweenawan wherever conditions were favorable. Thus considered they would be of Keweenawan age instead of post-Keweenawan, as has been supposed by Lawson.

Relations of the gabbro to the Logan sills.—The question of the relationship of the gabbro to the Logan sills has been discussed by Grant, who states that he "is inclined to separate the sills from the gabbro, but admits that this separation is not proven." The various facts which he considers

---

[a] Lawson, loc. cit., pp. 44–45.

[b] Geol. and Nat. Hist. Survey of Minnesota, Bull. No. 8, 1893, p. 47.

as evidence[a] against the relationship of the two kinds of rocks he summarizes as follows:

1. The sills are considerably altered, i. e., the pyroxene has usually largely been replaced by secondary minerals, while the gabbro is usually fresh and the olivine as well as the pyroxene is usually unaltered.

2. The sills are essentially nonolivinitic; at least traces of olivine, even when altered, are not common. The gabbro is normally olivinitic.

3. The sills are quite rich in ferromagnesian minerals, giving a dark-gray or black color to the rock. The gabbro is usually rich in feldspar and rather poor in ferromagnesian minerals, and the rock is light gray in color. When a basic mineral predominates, it is mostly iron ore, which is not the case with the sills.

4. The sills are in structure ophitic; the gabbro is granitic. This holds true also of the coarsest-grained sills and of the finest-grained gabbro. In this connection, it might be well to mention some sills in the Animikie at Akeley Lake in the Akeley Lake plate; these are apparently of gabbro. They are fine grained at their edges, but even here the structure is more nearly that of the gabbro, and not that of the ordinary sills.

5. The sills are very fine grained, almost glassy at the lower and upper sides, even in the thickest sills. The gabbro is not very fine grained at the contact with the Animikie rocks, and even on the edges of the apparent gabbro sills mentioned above, the fineness of the grain nowhere approaches that of the edges of the ordinary sills.

6. The sills, even the largest ones, have macroscopically altered the Animikie rocks for only a very few feet, or even inches, from the contacts, while the metamorphism of the Animikie at the gabbro contact is profound, extending for a distance of several rods.

7. The gabbro and sills have not been traced together, neither have they been found in contact. In the map the sills have not been shown in contact with the gabbro; this is on account of lack of exposures. They may, of course, come into actual contact with the gabbro.

8. Where the sills and the gabbro come nearest together the two rocks are easily distinguished, even in the field. The few specimens about which there is question have been, as far as examined microscopically, easily referred to one or the other.

In closing his summary Grant says that he is inclined to the idea that these sills are of earlier date than the gabbro.

Several years before the publication of the above statement Lawson expressed his opinion[b] that the sills are identical with many of the heavy sheets of dark diabase and gabbro which prevail on the eastern part of the Minnesota coast, and which are associated with the Keweenawan. The

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 488.

[b] Geol. and Nat. Hist. Survey of Minnesota, Bull. No. 8, 1893, p. 47.

writer is prepared to go much farther than Lawson, and to express the opinion that these sills are the equivalent in age of the Duluth gabbro of northeastern Minnesota, and even that they were derived from the same magma from which it was derived. In the following paragraphs Grant's statement, as quoted above, will be discussed and evidence will be presented to support the above-mentioned view of the intimate relationship of the sills and gabbro. This evidence was collected partly during work on the Vermilion district and during several reconnaissance trips into the Keweenawan gabbro from the Vermilion district, in the course of a portion of a season's field work on the Keweenawan of Minnesota and Canada, made in 1900.

No. 1. The sills are considerably altered, i. e., the pyroxene has usually largely been replaced by secondary minerals, while the gabbro is usually fresh and the olivine as well as the pyroxene is usually unaltered.

The facts are essentially correct, and no explanation can be offered for this difference, unless it is that it results from the sills being of smaller mass and intercalated in the slates and having been exposed in consequence to a more energetic action of water than has the gabbro. The gabbro disintegrates very easily, and even when the state of aggregation is such that the rock can be easily crushed in the hand the constitutents are relatively fresh. This gabbro, as a result of this readiness to disintegrate, has had its outer disintegrated portion removed by glacial action and water erosion. In general, erosion has kept pace with the disintegration of the gabbro. Hence the rock which we now observe is very fresh. The sills, on the other hand, are very much more resistant. All those examined were fairly fresh and exceedingly hard and tough. If one could get a specimen from the rocks of the sills deep down in the mass, doubtless the rock would be found to be about as fresh as the gabbro.

2. The sills are essentially nonolivinitic: at least traces of olivine, even when altered, are not common. The gabbro is normally olivinitic.

This is also true. But one must not neglect the fact that locally the gabbro is also practically free from olivine. The local absence of olivine in the gabbro is due to conditions of crystallization of the gabbro magma and possibly slight chemical differences also, and just in the same way can one explain the absence of olivine from the sills. No analyses have been made of the various facies of the gabbro to determine the chemical differences which may exist between them, nor have analyses been obtained of the rock of the sills to prove its identical chemical composition with the gabbro as a whole or with any of its special facies.

3. The sills are quite rich in ferromagnesian minerals, giving a dark-gray or black color to the rock. The gabbro is usually rich in feldspar and rather poor in ferromagnesian minerals, and the rock is light gray in color. When a basic mineral predominates, it is mostly iron ore, which is not the case with the sills.

The writer does not concur in this statement. The fact that the sills are generally darker than the gabbro is due largely to the finer grain of the sill rocks. When, however, the sills are very coarse grained one finds patches that are made up almost exclusively of feldspar in large individuals and such areas in the sills are a very light gray and become, when the feldspar is kaolinized, nearly snow white. On the other hand, some of the sections from the sills which have been examined are made up largely of magnetite, with pyroxene second in abundance, and last, the feldspar. This proportion of minerals is not the rule in the sills, but neither is it the rule in the gabbro, as witness the light-gray anorthosite with but little of the ferromagnesian compounds.

4. The sills are in structure ophitic; the gabbro is granitic. This holds true also of the coarsest-grained sills and of the finest-grained gabbro. In this connection it might be well to mention some sills in the Animikie at Akeley Lake, in the Akeley Lake plate; these are apparently of gabbro. They are fine grained at their edges, but even here the structure is more nearly that of the gabbro and not that of the ordinary sills.

The writer must disagree with the above statement of the texture of the rocks, as his own studies have shown that while the gabbro is predominantly granitic, nevertheless the ophitic texture is very frequent in the finer-grained facies. On the other hand, the sills show, in places where the rock is as coarse as is the finer-grained gabbro, a distinctly ophitic texture, grading into an imperfectly granular one, and from this down into very fine-grained intersertal textured basalts. A porphyritic texture which was not observed in the gabbros is common in the sills. These facts indicate a textural gradation between the gabbro and sills, the differences in general textural characters being due to the difference in the conditions between the slow crystallization of an enormous mass of magma, as in the case of the gabbro, and of a relatively small mass and quick cooling and crystallization, as in the case of the sills. This difference in the rapidity of cooling is shown also by the porphyritic structure of the rocks of the sills and the fine-grained rock occurring upon the edges of the sills. The relative rapidity of the cooling is further indicated by the feldspar phenocrysts which occur in the sills. These very commonly reach a length of 2 inches, with a maximum length of 4 inches. Had the magma cooled under the conditions under which the phenocrysts were formed, obviously the rest of the constituents would have also attained much larger size than they did, and the resulting rock would have been coarse grained and doubtless as granular as any of the gabbro.

But let us not neglect the evidence presented in the above-quoted statement itself—that offered in the statement that there are sills at Akeley Lake which are apparently of gabbro and not, like the other sills, different from the gabbro. Let us attempt to conceive of the conditions under which these sills were formed. They were injected into the sediments only a short distance away from the edge of the main gabbro mass, and have been traced parallel with this edge for a number of miles. Every observer of the rocks in which these sills lie intercalated states that the rocks are those which show the most extreme effects of the gabbro contact action. They are metamorphosed so that it is nearly impossible to determine their original character. Evidently they were exposed to the high temperature of the adjacent gabbro for a long time, and the magma of the sills must have profited by this high temperature of the parent mass of magma and the heated sediments when it was intruded, and cooled more slowly than it otherwise would have done, and much more slowly than the sills farther from the parent mass. Hence the sill rock approaches in its texture much more closely that of the parent mass of gabbro. No reason can be seen why these sills should be connected with the gabbro as gabbro sills and separated from the other sills in their vicinity, and even farther away, which occur under practically identical conditions, and show but relatively unimportant petrographic differences from them.

5. The sills are very fine grained, almost glassy at the lower and upper sides, even in the thickest sills. The gabbro is not very fine grained at the contact with the Animikie rocks, and even on the edges of the apparent gabbro sills mentioned above, the fineness of grain nowhere approaches that of the edges of the ordinary sills.

This difference in grain of the rock on the edge of the sill and of that on the edge of the main mass of the gabbro is the difference which normally occurs where there is such a great discrepancy in the size of the masses as there is in the case under consideration. Witness, for example, the character of the rock at the edge of any very large granite massive and that upon the edge of the dikes radiating from it. Undoubtedly, however, the gabbro is materially finer grained on the periphery of the mass than it is in the interior, and there is an imperceptible gradation between the fine and the coarse facies. Moreover, the border facies of the gabbro is about of the same degree of coarseness or possibly even less coarse than the rock occurring in the interior of the thickest sills. From the nature of the occurrence one should not expect the border of the gabbro to be as fine as the rock upon the edge of the sills.

6. The sills, even the largest ones, have macroscopically altered the Animikie rocks for only a very few feet, or even inches, from the contacts, while the metamorphism of the Animikie at the gabbro contact is profound, extending for a distance of several rods.

The relative intensity of the metamorphic action of the gabbro and sills depends largely, as does the size of the grain of the rocks, upon the masses of the magma, since this influences the rate of cooling. Of necessity a small mass of rock like a sill would have less effect upon the sediments than the gabbro.

One is better prepared to appreciate the difference in the effect of the sills and main gabbro mass when one thinks that the thickest sills are only about 400 feet thick, and that these are utterly insignificant when compared with the Duluth gabbro mass which covers about 2,400 square miles in Minnesota.[a]

7. The gabbro and sills have not been traced together; neither have they been found in contact. In the map the sills have not been shown in contact with the gabbro; this is on account of lack of exposures. They may, of course, come into actual contact with the gabbro.

It is true that no actual contacts of gabbro and sill have been observed, although they have been seen separated only by a short distance. At one place on the Duluth, Port Arthur and Western Railroad, between

[a] The geology of the Keweenawan area in northeastern Minnesota, III, Pt. II, Geology of the Keweenawan series, by A. H. Elftman: Am. Geologist, Vol. XXII, 1898, p. 132.

the first and second trestles east of Paulson's mine, there is a small mass of crumpled, much metamorphosed black slate, with the main mass of the gabbro to the south, and a small mass of gabbro to the north. This slate is considered by Grant to be an inclusion in the gabbro. The writer is inclined to think this slate is caught in the fork between the main gabbro mass and a sill which is an offshoot from it. Lack of exposures prevented the tracing of the connection between them. It must be said in this connection that in our work on the Vermilion iron district this relation between the gabbro and the sills was considered a problem of importance secondary to that of mapping the iron-bearing formations, and no especial attempt was made to trace the relation between these rocks in the field. It is believed that this connection would be shown to exist if the edge of the gabbro and the adjoining Animikie area were mapped in detail.

In this connection also it seems that the fact that the gabbro and sills have not thus far been found in contact could be used as evidence more strongly against the sills being older than the gabbro, as Grant[a] suggests, since the gabbro is found in contact with every other rock in the district which has been proved to be older than it is. If the sills are older than the gabbro, they would form the one exception.

8. Where the sills and the gabbro come nearest together the two rocks are easily distinguished, even in the field. The few specimens about which there is question have been, as far as examined microscopically, easily referred to one or the other.

Exception is taken to this statement, and the reader is referred to section 4 above, where certain sills are mentioned in these words:

In this connection it might be well to mention some sills in the Animikie at Akeley Lake in the Akeley Lake plate; these are apparently of gabbro. They are fine-grained at their edges, but even here the structure is more nearly that of the gabbro, and not that of the ordinary sills.

The rock of the sills can in general be readily distinguished from that of the main gabbro mass, but so can the dike rocks of rhyolite, etc., from the coarse granite of the massives from which demonstrably the dikes are offshoots. This difference is not evidence of importance against the relationship of the sills and of the gabbro.

---

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 488.

CONCLUSIONS AS TO AGE AND RELATION OF THE GABBRO AND SILLS.

In conclusion, there is presented the following summary of the facts observed which seem to indicate the true relationship between the gabbro and the Logan sills and their correct stratigraphic position. The gabbro and the rock of the sills are petrographically the same and textural gradations have been observed which indicate their close relationship. The gabbro, while predominantly coarse-grained and granular, is locally fine-grained and poikilitic, and in one place was found as a dike in the Keweenawan and there graded into a porphyritic facies and even into a fine-grained ophitic dolerite. The rock of the sills is in places, in the midst of the thick sills, a good granular gabbro in texture, and ranges from this through ophitic and poikilitic-textured dolerites into fine-grained aphanitic intersertal-textured basalts upon the selvage. Mineralogically they are the same, excepting that in the relatively few specimens from the sills which have been studied no olivine nor hypersthene has been observed, nor do the sills show such great mineralogic variation from titaniferous magnetite rocks to enormous anorthosite masses, although there are small anorthosite masses in the sills. Such differences in variation are, however, easily explicable as due to the enormous difference existing between the masses of magma forming the gabbro and that forming the individual sills.

It is admitted by all that both the gabbro and the sills are younger than the Upper Huronian, since they both have been observed at numbers of places to cut the rocks of this age. The point of difference is the relationship between the gabbro and sills and the Keweenawan. The writer found the gabbro cutting a portion of the Keweenawan rocks, whose exact stratigraphic position with relation to the remainder of the Keweenawan is, however, not known, and hence considers it and the sills as younger than some of the Keweenawan.

The gabbro is believed to be a great laccolitic mass which in general follows approximately the contact plane between the Animikie series (Upper Huronian) and the Keweenawan. In the Vermilion district there are local departures from this which will be described in the following paragraph.

Over a great part of the southern edge of the Vermilion district the gabbro followed essentially along the plane between the Upper Huronian (Animikie) and the lower lying sediments, uplifting thereby the Upper

Huronian sediments, for at several places on the edge of the Vermilion district and just south of it are found isolated patches of the lowest part of the Gunflint formation (Animikie) included in the Keweenawan gabbro. The gabbro in this part of the district may originally have been completely covered by the Animikie series, but in this part of the district, also, the rocks are much more closely folded than in the east near Gunflint and in the west in the Mesabi district, and as a result of the erosion in this area, where the rocks have been folded and fractured, all of the Upper Huronian (Animikie) but the few included patches has been removed.

In the eastern part of the Vermilion district the gabbro began to rise and cut across the Upper Huronian, reaching higher and higher beds to the east, and then spread out essentially along the plane between the Upper Huronian (Animikie) and the base of the Keweenawan, sending sills and dikes into the Rove slates of the Upper Huronian and also into the Keweenawan rocks, as can be seen on Brulé Lake.

The writer is inclined to believe that the gabbro is a great basic igneous mass which represents a basic differentiation product of a magma from which perhaps the major portion of the Keweenawan volcanics were derived, and which basic magma has, perhaps, as its complementary acid rocks, the great mass of intrusive "Red Rock" and the related rhyolite flows of the Keweenawan.

METAMORPHIC EFFECT OF GABBRO AND SILLS.

The effect of the gabbro upon the various rocks with which it is in contact has been considered under the description of those various rocks, for example, under the Ely greenstone, the Rove slates, etc., but a brief summary statement will be made here concerning the character of this metamorphism. The most noticeable general effect of the gabbro has been to produce a very large quantity of rich brown biotite in the rocks in contact with it.

Archean (*Ely*) *greenstones.*—In the meta-dolerites and meta-basalts (greenstones) the general effects are much the same as in the case of the sediments. The ophitic texture of those greenstones which have been studied is still retained with a fair degree of distinctness. There is, however, a tendency to gradually destroy the texture and produce granular rocks therefrom by the production of large quantities of biotite, with hypersthene, augite, brownish-green hornblende, and magnetite, and possibly the recrystallization of the feldspar.

Lower Huronian.—In the Lower Huronian sediments this production of biotite has been accompanied by a recrystallization of the minerals of the rock, whereby the sedimentary structures are mostly destroyed and mica-schists and gneisses are produced. Immediately along the edge of the contact with these schists in the metamorphosed sediments occur large quantities of ferromagnesian minerals, such as augite, hypersthene, and brown hornblende. In the case of the conglomerates we find, since there are a number of different kinds of pebbles, and these differ from the matrix in which they lie, that the pebbles when affected furnish a somewhat different product from the matrix, and this product usually stands weathering better than the matrix, so that the pebbly character of the conglomerate is retained.

Upper Huronian (*Gunflint formation*).—Where the gabbro has been in contact with or very near the rocks of the iron-bearing Gunflint formation, it has affected them in a very marked way, and has produced magnetite ores interlaminated with bands of quartz and a rock composed of olivine, hypersthene, augite, hornblende, and magnetite, with quartz in varying proportions. The rocks thus produced are different from any original igneous or sedimentary rocks with which the writer is acquainted.

Rove slates.—The metamorphism of the Rove slates by the gabbro has been such as to produce, from rocks consisting of angular grains of quartz, feldspar, and plates of chlorite, and a dark interstitial material, more or less completely crystallized mica-schists, or, with larger percentage of feldspar, mica-gneisses, if these terms can be applied to rocks that have an essentially granitic texture, although the original banding of the sediments remains in the recrystallized rock and causes it to break more readily along these bands than in any other direction.

The action of the sills is very slight upon the slates, in most cases producing rocks which are mica-schists, but not so completely recrystallized as in the case of those affected by the gabbro.

Endomorphic action—There is, along the margin of the gabbro, a somewhat finer grained facies than further in the mass. The sills also show distinct selvages, but neither the gabbro nor the sills appear to have had their textures or general characters otherwise modified as a result of contact with the various rocks mentioned.

IRON-OXIDE BODIES IN THE GABBRO.

It has been known for a long time that there were iron-oxide masses in northeastern Minnesota within the area which is underlain by the great Keweenawan gabbro mass. One of these, which occurs on Mayhew Lake, was seen and described by Chauvenet in 1883 and 1884,[a] and since that time there have been a number of brief mentions made of these gabbro iron-oxide masses in the various papers on the geology of Minnesota to which reference has been made in this chapter. The iron oxide occurs in bodies of varying size and the existence of these bodies has aroused a considerable interest among investors.

CHARACTER, OCCURRENCE, AND ORIGIN OF THE IRON-OXIDE BODIES.

These bodies consist of titaniferous magnetites, and have, according to H. V. Winchell,[b] the following composition:

Analyses of iron-oxide bodies.

Constituents.	I.	II.
Silica, SiO_2	2.02	20.90
Alumina, Al_2O_3	2.68	1.75
Titanium binoxide, TiO_2	12.09	2.23
Magnetic oxide of iron	80.78	70.29
Protoxide of iron	....	2.01
Chromium sesquioxide, CrO	2.40	....
Magnesia, MgO	....	2.63
Lime, CaO	Tr.	Tr.
Phosphoric acid	.03	None.
	100.00	99.81
Metallic iron	58.48	52.46

In view of the fact that a great deal of money has been spent in this district in exploring for nickel ore, which has been reported as occurring in the titaniferous magnetites in the gabbro, the following statement by Grant is valuable:

Nickel does occur in similar situations,[c] and is frequently found as an impurity in one of the gabbro minerals (olivine), but as yet no reliable reports of nickel ore

[a] W. M. Chauvenet, U. S. Geol. Survey, manuscript notes.

[b] Geol. and Nat. Hist. Survey of Minnesota, Bull. No. 6, 1891, p. 141.

[c] This evidently has reference to its occurrence in other districts; not in Minnesota, however. Clements.

rich enough for mining have been received. A determination of the nickel in iron ore from the locality of the specimens above analyzed showed less than one-half of one per cent.[a]

The iron-oxide bodies occur in the midst of massive granular normal gabbros, and are not separated from the gabbro by sharp lines. The titaniferous magnetite body on the margin of any outcrop next the gabbro is lean, and has a large proportion of pyroxene, olivine, and feldspar, in general of gabbro minerals, mixed with the titaniferous magnetite. These minerals become fewer toward the main magnetite mass, but in the direction of the gabbro they increase in quantity, first giving varieties of highly magnetitic gabbro, but gradually passing into the crystalline gabbro, with black and gray mottlings. There is then a transition from the gabbro into the titaniferous magnetite bodies, which are but very magnetitic portions of the gabbro.

The high percentage of titanium in the magnetite bodies, as shown by the above analyses, is very important from both the economic and the scientific standpoint. In the first place, the titanium renders the magnetite at present valueless, since, in the present iron-smelting practice, titaniferous ore can not be smelted economically. The magnetites can, therefore, not compete now with the cheap nontitaniferous ores, nor can they in the future, unless new discoveries give a higher value to titaniferous ores, or cause changes in iron smelting which will place the titaniferous ores on an even basis with the other iron ores.

The injurious effect of the titanium in rendering the magnetite unmarketable would, of course, apply to these titaniferous magnetite bodies, whatever their size. However, so far as we know, up to the present time no published description has been given of any large continuous masses of the practically pure titaniferous magnetite.

The content of titanium is of interest from a scientific standpoint, in that it gives evidence (additional to that offered by the occurrence) of the intimate connection between the gabbro and the ore, and enables us to determine its source. The gabbro contains everywhere titaniferous magnetite in small quantities, and the large amount collected in these magnetite bodies owes its accumulation to those little understood processes generally spoken of as processes of segregation. As the result of these processes the titaniferous

[a] Loc. cit., p. 62.

magnetite elsewhere widely disseminated in small quantities through the gabbro was locally concentrated, while the magma was in a more or less fluid state. We conclude that these titaniferous magnetite bodies belong to those iron-ore deposits of igneous origin, which are at present of little value. All of the other ore deposits of this district, even when now magnetitic, as in the case of the Gunflint ores, are nontitaniferous, or contain only traces of titanium, and were originally of sedimentary origin.

SECTION II.—ACID DIKES YOUNGER THAN THE DULUTH GABBRO.

The great Keweenawan gabbro mass is cut through at various places by small dikes of red granite. Several of these were seen beyond the limits of the Vermilion district. One especially was noted upon the island on the east side of Cross River, just opposite the bay into which the portage from Snipe Lake enters. This dike is 3 feet in width and trends north and south. It is a fresh biotite-granite. Grant[a] reports a granite dike cutting through the gabbro on an island in Gobbemichigamma Lake in the NW. $\frac{1}{4}$ of the NE. $\frac{1}{4}$ of sec. 6, T. 64 N., R. 5 W. These occurrences are sufficient to prove that there is a granite later than the gabbro.

South of the Vermilion district there are large areas underlain by a bright-red weathering acid rock, varying from syenite to granite, which sends off shoots into the adjacent gabbro. No attempt has been made to trace the connection between the granite dikes mentioned above and these larger masses of "red rock" occurring in the midst of the Keweenawan. The possibility of their close relationship is suggested, however.

SECTION III.—BASIC INTRUSIVES YOUNGER THAN THE DULUTH GABBRO.

At numerous places basic dikes have been noted in the gabbro. These were found as the result of the limited studies made upon the gabbro. These studies were confined chiefly to the margin of the gabbro and to a few excursions made within the Duluth gabbro mass. Unquestionably great numbers of other dikes of similar character would have been found had the gabbro been more closely examined. A number of basic dikes were also found in the Upper Huronian sediments and in the older rocks of the Vermilion district, both the eruptive and sedimentary ones. These dikes correspond in every detail with those found in the gabbro. All of these very

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 479.

fresh rocks are basalts or dolerites, and are believed to belong to the same general period of formation.

The distribution of these dikes can be seen on the maps in the accompanying atlas, where those of sufficient size to warrant it have been shown. The majority of the dikes are small and have been omitted in most cases, although a few have been inserted upon the map but are greatly exaggerated. These dikes cross the strike of the slate and other sediments and are also found to run parallel to their bedding. In some of the schistose rocks the dikes very clearly followed the schistosity.

The dikes can not be said to follow a definite system in their occurrence, although presumably if they were studied in sufficient detail it would be found that they followed in general the lines of fracture which prevail in those portions of the district in which they occur.

PETROGRAPHIC CHARACTERS.

Macroscopic characters.—The rocks are invariably dark colored, black or greenish or brownish black. The rocks in the smaller masses, the narrower dikes, show a very fine grain and could properly be called basalt. The rocks in the centers of the larger dikes show up as coarse-grained ophitic textured rocks and are dolerites. However, gradations between the fine- and coarse-grained forms are shown in that the finer-grained phases appear upon the margins of the large dikes grading up by increasing size of mineral constituents to the coarse-grained dolerites, occupying the centers of the large dikes. The fine-grained basalts seem to predominate.

Microscopic characters.—Under the microscope, the rocks are found to be very fresh, as one would infer from the fact that they are usually decidedly black. In some few of them slight alterations producing greenish or brownish-green minerals tend to vary these to the brown or greenish tones already referred to. The constituents of the rock are yellowish to violet augite, green hornblende, a feldspar near labradorite in composition, olivine, apatite, ilmenite, and magnetite. These minerals show their normal characters and but rarely give evidence of being altered. Where altered there has been produced chlorite, epidote, calcite, and hornblende. The ophitic texture predominates in these rocks, although the intersertal texture is also common and merges at places into an imperfect fluidal texture brought out by the parallel arrangement of the feldspars. Some of the rocks are porphyritic.

RELATIONS TO ADJACENT FORMATIONS AND AGE.

These basic rocks wherever found are clearly intrusive in the rocks which surround them. Hence, in all cases the rocks are younger than those in which they occur. These dikes cut all the rocks of the district from the Archean up to and including the Keweenawan gabbro, but have not thus far been found cutting the granite dikes which were found in the gabbro in the Vermilion district. However, in the Keweenawan area south of the Vermilion district similar basalt dikes have been seen cutting through the syenite and granite massives referred to above, and it is strongly probable that these dolerite dikes are of the same age. Since, then, these intrusives cut all other rocks of the district they must be the youngest of the pre-Cambrian rocks which are represented.

METAMORPHIC EFFECTS.

In several instances where the contacts between the Rove slates and the dikes were exposed, observation showed that the slates were indurated in the vicinity of the dikes, this induration diminishing as the distance from the dikes increased. Special observations would be required to determine accurately the character of the metamorphism which produces the induration. These examinations were not warranted by the amount of time available for the study of the district, consequently the details of this change must be left for future studies. In all probability this change consists in the recrystallization of the quartz and feldspar and the production of biotite, as is found to be the case in the contacts of the Logan sills and dikes upon the same slates.

CHAPTER VII.

THE DRIFT.

The Vermilion district, like all the rest of the Lake Superior region, was overridden by the great ice sheets of Glacial time. The tendency of the glacial action during the advance of the ice sheet was, of course, to reduce this district to a general level, to round the hills, and produce striæ upon the rock surfaces, thus marking the direction of its movement. In its retreat this process of leveling was continued by the filling in of the pre-Glacial valleys with morainal deposits. While it is known from the researches of the glacialists that the Lake Superior region, and of course that part of it here discussed, was covered several times by ice sheets, we can recognize in the Vermilion district the effects of the ice only during the last or Wisconsin stage of the Glacial epoch, to which consequently belong all of the deposits which will be briefly described.

According to Prof. J. E. Todd, the glacial deposits of northeastern Minnesota can be referred "to two great lobes of the ancient ice sheet, a shorter one moving southwest through the Lake Superior Basin, and a longer one moving around this from the northeast to the west and southwest."[a]

In order that the reader may get a clear idea of the glacial history of the Vermilion district, it may be well to make some general statements concerning the glacial history of that portion of Minnesota which is adjacent to but outside of the district considered in this paper. Extending in an approximately northeasterly direction through northeastern Minnesota there is a height of land which forms the watershed between the hydrographic basins of Lake Superior on the south, belonging to the continental St. Lawrence basin, and between the basin of the Rainy River and Lake of the Woods, which belongs to the great Hudson Bay basin on the north. This

[a] A revision of the moraines of Minnesota, by J. E. Todd: Am. Geol., Vol. XVIII, 1896, pp. 225–226, a paper read at the August meeting of the American Association for the Advancement of Science, before Section E, Geology and Geography. Also, Am. Jour. Sci., 4th ser., Vol. VI, 1898, p. 473.

height of land may be subdivided into several minor ridges following the general trend indicated. During its greatest advance the Lake Superior lobe and the ice lobe to the north, called by Elftman[a] the Rainy lobe, were confluent. As the ice receded these lobes became separated, their separation being determined by the high land just mentioned as lying north of Lake Superior. For a time they were close together, forming an interlobular moraine. As they receded and became more widely separated, each formed independent moraines.[b] Between these moraines there occurred V-shaped areas, with the apex of the V pointing to the northeast, the arms becoming more widely separated as they are followed to the west.

No deposits of the Lake Superior lobe are known in the Vermilion district. There has been recognized, however, and described by Upham,[c] a great moraine deposited by the Rainy lobe, which has been named by him the Vermilion moraine. Moreover, the records of striæ collected by Upham[d] and inserted on his map in the same article show the direction of the ice flow to have been in the main to the south-southwest, varying from S. 10° to S. 50° W., and seem to corroborate Todd's division of the ice sheet in this region into the two lobes as mentioned above. Since Upham's work this Vermilion moraine has been further described and more accurately delimited by Elftman.[e] No special study of the glacial deposits of the Vermilion district has been made by the United States geologists, as the work in this district was primarily undertaken with the object of determining the pre-Glacial geology. Nevertheless, observations made in the course of the survey enable us to add a little to the knowledge of the course in detail of this moraine. These observations have been made use of, and accordingly the moraine has been traced as is shown on the accompanying map (fig. 23. At the time of the formation of the moraine the ice in the northeastern portion of the district passed over this east end of the Giants range, and the moraine was deposited to the south of it. As we follow

[a] The geology of the Keweenawan area in northeastern Minnesota, by A. H. Elftman: Am. Geol., Vol. XXI, Feb., 1898, p. 108.

[b] Todd, op. cit., Am. Jour. Sci., 4th ser., Vol. VI, 1898, p. 473; Elftman, op. cit., pp. 90–108.

[c] Preliminary report of field work during 1893 in northeastern Minnesota, chiefly relating to the glacial drift, by Warren Upham: Geol. Nat. Hist. Survey of Minnesota, Twenty-second Ann. Rept., 1893, pp. 18–66.

[d] Upham, op. cit., pp. 38–40.

[e] Elftman, op. cit., p. 94.

the moraine westward we find, however, that it gradually approaches the Giants range, which has a trend to the south of west, and crosses it in T. 63 N., R. 9 W. West of this point the ice tongue reached a point considerably farther south, and it had sufficient strength to advance well up the slopes of the range, but was never able to surmount it. From here on the moraine is found lying first high up upon the northern slope of the range, with the distance increasing between it and the range as we go farther west. In the western portion of the district it is nearly 15 miles north of the range.

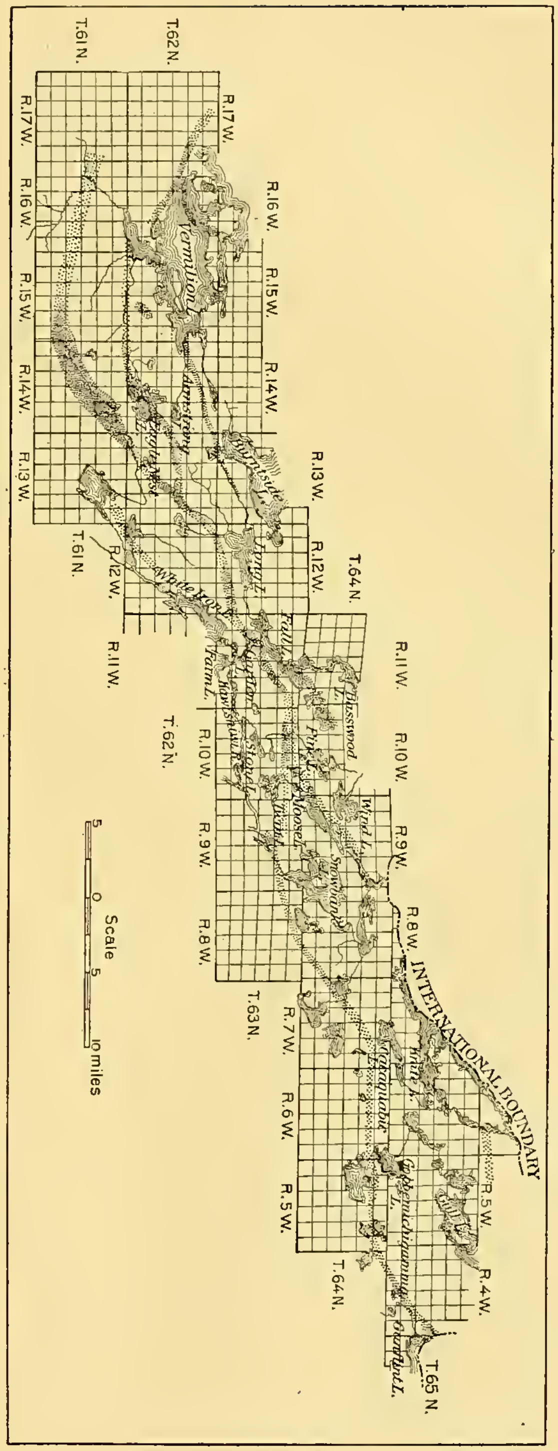


Fig. 23.—Sketch map showing distribution of the Vermilion moraine in the Vermilion district of Minnesota.

Exceptionally heavy deposits of drift are known to occur in the following areas: Secs. 21–28, T. 61 N., R. 15 W., and extending from there on up to the northeast in a belt approximately 2 miles wide through secs. 19, 30, 18, 29, 16, 21, 10, 15, 22, 2, 11, 14, 1, 12, T. 61 N., R. 14 W.; sec. 6, T. 61 N., R. 13 W.; secs. 14, 15, 22, 23, T. 62 N., R. 13 W.; secs. 25, 26, 34, 35, 36, T. 63 N., R. 12 W.; secs. 30, 31, T. 63 N., R. 11 W.; secs. 20, 21, 16, 15, 14, 11, 12, T. 63 N., R. 11 W.; secs. 3, 4, 5, 8, 9, 10, T. 63 N., R. 10 W. The main moraine has been traced by connecting up these heavy drift deposits. Its distribution can be seen in fig. 23. In the eastern portion of the area the course of the moraine is essentially that as given in Elftman's paper, referred to above, with but a few minor changes. This main moraine is not, however, the only moraine which is present in this district. There are several other areas which have been observed in which a clearly developed kettle moraine topography is present. Such a series of areas have been connected extending from near the south shore of Vermilion Lake to the north of east, running approximately along the town line between Ts. 61, 62 N., Rs. 14, 15 W., and then extending to the northeast across Eagle Nest lakes into the western portion of T. 62 N., R. 13 W. This small moraine is for the greater part of its extent nearly parallel with the main Vermilion moraine. In the east, however, it approaches the moraine, and finally coalesces with it. It is evidently a moraine representing one of the stages in the recession of this lobe during which this extreme southwestern portion of the lobe in the lower land retreated relatively much more rapidly than did the southeasterly margin of the ice. Still another stage in the recession is represented by morainal deposits extending from north of Armstrong Bay of Vermilion Lake northeast through the northern portion of T. 62 N., R. 14 W., and the southern portion of T. 63 N., R. 13 W., south of Burntside Lake. Still other deposits were observed on Birch Point and on Pine Island, in Vermilion Lake. These could probably be traced to the northeast of Vermilion Lake, but no special work having been done in this area the continuation of these deposits is not known. Other terminal moraine deposits north of the main Vermilion moraine are known to occur in the southern portion of T. 64 N., Rs. 9, 10 W.; in the southwestern portion of T. 64 N., R. 9 W., north of Moose and Newfound lakes; and in the southern part of T. 66 N., Rs. 5 and 6 W., to the northwest of West Gull Lake.

Over the remainder of the district the drift is comparatively thin, and in fact in places only a few bowlders on the tops of the hills with occasional striæ and the rounded outline of the hills indicate the former presence of the ice sheet. The thinness of this drift is especially noticeable in the eastern part of the district. In the western portion of the district the general drift mantle is much thicker than it is in the eastern portion. The general effect of this drift is, of course, to cover all of the rocks, and in agreement with the distribution given above we find that in the western portion of the district exposures of rock in situ are far less numerous on the whole than in the eastern part, where the drift was apparently much thinner to begin with, and where since the original pre-Glacial relief was more marked, it has to a considerable extent been removed from the crests of the hills by post-Glacial erosion, which is there correspondingly more vigorous.

The width of the Vermilion moraine proper can not be given with any very great degree of accuracy. It varies considerably, ranging from a half mile, and perhaps even less, up to between 2 and 3 miles in T. 61 N., R. 14 W.

The depth of the drift constituting the moraine is also variable. Test pits and drill holes have cut through it in a number of places to a depth of 75 feet. It is, of course, in many places much thinner than this. Judging from the very considerable irregularities noticed—for instance, in the area southwest of Eagle Nest lakes, along the township line between Ts. 61 and 62 N., R. 14 W., and in the moraine extending northeast-southwest across T. 61 N., R. 14 W., and also in the area southeast of Ely—it must run up to at least 150 to 200 feet in depth, and may even reach a greater thickness than this.

Between the south edge of the moraine and the Giants range, especially in Ts. 60, 61 N., Rs. 14, 15, and 16 W., extensive deposits of drift, modified by the waters from the edge of the melting glacier, are well developed. To the north of the moraines in various places similar modified drift is found, which evidently owes its origin to the modification by water from the Rainy lobe after it had passed to the north of the Vermilion moraine.

It will be remembered that the drainage of this district, which is approximately bounded on the south-southeast by the high land of the Giants range, is to the northwest. It is to be supposed that as the glacier retreated the waters from its melting edge must have been dammed between this range and the ice lobe to the north. It seems highly probable, therefore, that glacial lakes of considerable size must have been formed in the Vermilion district. A study of the topography shows that there are many areas which must have been favorable for the development of such lakes, but no definite evidence, such as lake beaches and clay deposits, pointing to the existence of large glacial lakes, has been found. It seems highly probable, however, that such lakes existed on the site of what is now Vermilion Lake, Basswood Lake, and Saganaga Lake, and probably in many other places. Indeed, Winchell and Grant[a] have reported terraced gravels around Long Lake and White Iron Lake, which give clear evidence of the existence of lakes at these places during Glacial time, when the water was considerably higher than the present water level and which consequently covered larger areas than those of the present lakes. Winchell[b] has recently, since the above was written, given a brief description of the glacial lakes which occur partially or wholly in the Vermilion district.

According to him, Lake Annamani covered the present site of Vermilion Lake, being 10 or 15 feet higher than it is. Lake Norwood was south of the present Vermilion Lake, and covered the low flat area north of the Giants range along the Embarrass River.

---

[a] Geol. and Nat. Hist. Survey of Minnesota, Final Rept., Vol. IV, 1899, p. 235.

[b] Glacial lakes of Minnesota, by N. H. Winchell: Bull. Geol. Soc. America, Vol. XII, 1901, pp. 125-126.

CHAPTER VIII.

TOPOGRAPHY OF THE DISTRICT IN ITS RELATION TO GEOLOGIC STRUCTURE.

The relationship of topographic relief to geologic structural features is probably nowhere better brought out than in the Vermilion district. From the preceding pages the reader will have learned of the gabbro plateau (pp. 37, 399) with its simple topographic features due chiefly to the homogeneous character of the gabbro, the country rock, and of the peculiar topography of the sawtooth hills area (pp. 38, 391, 400) due to the presence of the sills intercalated between the beds of slates with their monoclinal dip to the south-southeast. The descriptions which follow apply especially to the broad area north-northwest of the Giants range and to the Giants range itself.

In these portions of the Vermilion district the rocks are closely folded into synclines and anticlines, frequently arranged en echelon, which, in general, have an east-northeast trend. Moreover, the oldest rocks are the hardest, and these usually occupy the anticlines; whereas the troughs are occupied by the younger, softer rocks. The minor structures, such as cleavage and fissility, are in general parallel with the above structural arrangement. As a consequence of the combination of these factors, which are of the greatest importance in determining the topography, we find the main ridges to be usually anticlines of older rock, with the intervening valleys in synclines of younger and less resistant rocks. Almost without exception the main ridges and valleys, and to a very great extent the minor ones also, agree with the trend of the geologic structure and run east-northeast.

Beautiful examples of the relationship between the topography and geologic structure are shown in the cases of Tower and Lee hills at Tower and of Soudan Hill at Soudan. Here the anticlinal hills of resistant

Archean jasper are surrounded by valleys in the softer rocks of Lower Huronian age. The numerous anticlinal hills of Archean greenstone between Moose Lake and the Kawishiwi River, in Ts. 63 and 64 N., R. 9 W., and those between Knife Lake and Gobbemichigamma Lake, in Ts. 64 and 65 N., Rs. 6 and 7 W., show similar relationships, being surrounded by sedimentaries of Lower Huronian age. Somewhat less characteristic are the numerous small anticlines shown on the islands of Vermilion Lake and the adjacent shores, with Ely Island, the point south of Mud Creek Bay, and the point east of Stuntz Bay as the most striking cases. Just across the international boundary in Ontario there is an area reconnoitered by the United States geologists where a great Archean anticline is found separating the Lower Huronian Knife Lake slates from the Archean iron-bearing Soudan formation in Emerald and Big Rock lakes, and another Archean anticline separates the iron formation of these last two lakes from the Lower Huronian syncline in That Mans, This Mans, the Other Mans, and Agawa lakes. These four narrow, aligned lakes are the most striking cases of synclinal lakes found in this region.

The shapes of the lakes depend also to a very great extent upon the structural features of the rocks surrounding the lakes. They lie, as has already been intimated, in structural basins which are occupied by the younger rocks. Examining the large lakes in detail one finds that the prominent salients are formed by the anticlines of older rocks, while the reentrants are synclines occupied by the younger ones. This condition is very noticeable on the east end of Vermilion Lake. Beginning at the south with Stuntz Bay we find the east side of this bay, which continues to the east in a marked depression, is in a syncline of Lower Huronian sediments with an anticline of Archean greenstone and jasper forming Soudan Hill to the south, and a corresponding anticline of Archean jasper to the north, which forms a salient. The western side of the bay shows clearly the relation between the differential erosion of rocks of the same series. It lies in a syncline of Lower Huronian slates with the underlying conglomerate of the same series forming the north arm, and Archean jasper with occasional patches of unremoved Lower Huronian conglomerate forming the south arm. Armstrong Creek and Bay is another case of a syncline occupied by the Lower Huronian slates with Lower Huronian conglomerates on both flanks, and forming ridges Still farther south and north of the conglomerate come anticlines of Archean rocks. Mud Creek, about a mile and a half north of Armstrong Bay, flows also in a depression occupied by the Lower Huronian sediments, which are flanked by Archean greenstone. Similar cases are shown in the synclines of sediments extending from Vermilion eastward to Bass Lake, in sec. 2, T. 62 N., R. 15 W., and extending eastward along Rice Bay of Vermilion Lake, in secs. 34 and 35, T. 63 N., R. 15 W., still farther north.

In T. 64 N., R. 9 W., Moose Lake occurs, lying in a syncline of Lower Huronian slates. On the west side of the northern bay of Moose Lake, that one out of which the portage to Wind Lake goes, the salient on the west side is formed by an Archean greenstone anticline with reentrants on both sides in the Lower Huronian slates. Knife Lake shows a beautiful case in the 2-mile long point of Archean greenstone projecting west through secs. 22 and 23, T. 65 N., R. 7 W. Both to the north and south of this erosion has very nearly removed all of the Lower Huronian sediments from contact with this anticline, small patches only being found on the north and south flanks, as shown on the geologic maps in the accompanying atlas. Lake Gobbemichigamma, in secs. 31–32, T. 65 N., R. 5 W., and sec. 6, T. 64 N., R. 5 W., and sec. 1, T. 64 N., R. 6 W., lies right at the junction of three great formations and is influenced in its shape very markedly by them. On the shores each formation shows the topographic forms characteristic of it. The formations meeting here are the Archean greenstone and the Lower Huronian Knife Lake slates, which overlap upon the greenstone, and in contact with both of the above and overlapping them is the Keweenawan gabbro. The Twin Peaks Archean anticline forms a bold east-west ridge, the end of which overlooks the lake and projects into it from the west, forming two salients. The slight embayment to the north of this greenstone is along the contact of the Archean and the Lower Huronian slates, while the embayment to the south follows a little to the south of the contact of the Archean greenstone and of the Keweenawan gabbro. The greenstone runs down in a very steep slope to the water. The north side of the lake is bounded by the slates, and here there is a gentle slope down to lake level. On the southeast and south sides of the lake the gabbro appears in steep cliffs and prominent headlands, the irregularities of the shore being influenced in their trend by the marked jointing of the gabbro.

The shapes of many of the lakes, especially those which lie completely in rocks of more or less uniform character, have been determined by the direction of the joint planes of the district. The major joints agree very closely with the direction of the predominant schistosity and trend N. 60–80° E. The next important system of joints is approximately at right angles to that direction. The effect of this jointing can be seen best in the lakes lying within the well-jointed Knife Lake slates. Knife Lake itself shows its dependence upon the jointing of the rocks by its principal direction, which agrees with the jointing, and by the occasional arms nearly at right angles to it. The main southeast arm of Knife Lake owes its direction, as can be readily seen by reference to the maps in the atlas, to the influence of the Archean anticline which forms its north shore. The lakes between the east end of Knife Lake and Saganaga Lake are within the area wherein the influence of the anticline formed partly of the granite of Saganaga Lake makes itself felt, and where as a result of this the bedding of the slates, as well as the jointing, which agrees fairly well with the direction of bedding, turns strongly to the east of north, getting more nearly north, and finally turning a little to the west of north as the northern portion of the granite mass is approached. This change in direction of the structure in the slates and the relationship of the extension of the lakes thereto is shown by the string of lakes in secs. 26, 34, and 35, T. 66 N., R. 6 W., and secs. 3 and 10, T. 65 N, R. 6 W. This string of lakes connecting the east end of Otter Track Lake and the east end of the south arm of Knife Lake has a trend in general of N. 20° E. Another specific instance of the influence of the jointing in these slates can be seen in the lakes in sec. 30, T. 66 N., R. 5 W., and secs. 24–25, T. 66 N., R. 6 W., just west of the boundary between the Knife Lake slates and the granite of Saganaga Lake. Here the jointing and the bedding have turned to about N. 10° W. These two lakes have their major direction following this line of major jointing. A second system runs N. 25° E. and controls the trend of the ends of some of the points and the greatest width of the lakes.

Another factor which has in many cases determined the position of the topographic features has been the plane of contact between the different formations and the differential erosion of these formations. A notable case is that of Otter Track Lake, on the international boundary. This lake lies along the contact of the Archean greenstone and the Lower Huronian Knife

Lake slates. The factor of differential erosion was aided here by the strike of the slates and the jointing, which agrees closely with the strike of the line of contact. Only in one place has any of the Lower Huronian slates been left upon the north side of the main arm of the lake. Before reaching the east end of this lake there is a large north-trending bay which is in Canadian territory. The direction of this bay has been controlled, like that of the main body of the lake, by the contact of the Lower Huronian slates and the Archean formations which here swings sharply to the north.

In the western part of the district, extending from Rice Bay of Vermilion Lake, in T. 63 N., R. 15 W., over sec. 36, T. 64 N., R. 12 W., over nearly to Basswood Lake, there is an almost continuous line of lakes and streams marking the boundary between the Archean greenstone and those schists which have been produced from this greenstone by the metamorphic action of the Trout, Burntside, and Basswood granites upon it. This line begins near Rice Bay, as mentioned above, and can be followed east through the creek flowing into this bay from the east nearly to the vicinity of Mud Lake in sec. 3, T. 62 N., R. 14 W. For a few miles then it runs south of Burntside Lake. From sec. 32, T. 63 N., R. 13 W., it is followed approximately by Burntside River up to sec. 24 of above township and range. From there on to the east it follows approximately a string of lakes—Little Long Lake, Bass Lake, and Mud Lake. Another striking instance of this influence of the contact of two rocks on the topography is shown in the case of the Kawishiwi River. Beginning in sec. 15, T. 63 N., R. 9 W., where it enters the Vermilion district, it runs southwest very closely along the contact between the gabbro and the Lower Huronian sediments. Then when the sediments disappear it runs along the contact between the Archean greenstone and Keweenawan gabbro, and where the Giants Range granite commences it follows the contact between the gabbro and the granite. Shortly after the granite is reached the Kawishiwi divides in sec. 26, T. 63 N., R. 10 W., the south arm running southwest very closely along the granite-gabbro contact. The north arm of the Kawishiwi continues very nearly due west, following along the contact between the granite and the schists produced by the contact action of the granite on the Archean greenstone; then between the greenstone and the overlying Lower Huronian sediments, and finally bends northwest, cutting across the greenstone. In the eastern part of the district, in secs. 34 and 35, T 65 N., R. 5 W., a string of lakes connected by a stream is found along the contact between the iron formation of the Lower Huronian and the Lower Huronian Ogishke conglomerates. A similar topographic depression can be followed between the contact of the granite and the greenstones in secs. 26, 27, 28 and 29, T. 62 N., R. 13 W., and in secs 17, 9, 3, 11, and 1, T. 62 N., R. 12 W., to sec. 31, T. 63 N., R. 11 W., south of Ely.

The above-mentioned instances are only some of the more important and most noticeable of the many cases which occur in the Vermilion district, and which might be cited as illustrating the dependence of topography upon geologic structure. Some of the other cases have been referred to in the more detailed descriptions of the various kinds of rocks and of the special areas.

CHAPTER IX.

GEOLOGIC HISTORY OF THE VERMILION DISTRICT.

The earliest period of the history of this district, as of all others, is entirely hidden from us. We can go no farther back than the time of the formation of the earliest rocks now exposed to view. Whether during this early time the area of the Vermilion district remained continuously under water after the formation of the primeval ocean, or after an ocean existed there was a land area antedating the development of the oldest rocks now found, can only be conjectured. However this may be, the evidence we now have indicates that this region was for the most part, if not wholly, under water at the time the Ely greenstones were formed.

The Ely greenstone, as has been shown, consists entirely of igneous rocks. These are almost wholly lavas and largely of ellipsoidal greenstones which are amygdaloidal and spherulitic, and are therefore presumed to be surface igneous rocks. These greenstones within the district have a great but unknown thickness, and the formation extends far beyond its confines in a continuous belt nearly to Lake Nipigon, Ontario. Furthermore, similar formations occupy equivalent positions in other parts of the Lake Superior region; hence we infer that the time of the deposition of the Ely greenstone was one of regional vulcanism paralleled in magnitude only by the more important later volcanic periods, such as those of the Keweenawan and the Tertiary.

The length of time involved in the formation of the Ely greenstone can only be conjectured. It is well known that volcanic material accumulates with great rapidity; hence, so far as the masses of material exposed to view may determine our judgment, we would not be justified in concluding that this period was one of extraordinary length. However, if we unite the events preceding the time of the Ely greenstone with that of the greenstone itself the time thus represented would be very long indeed. This time is only a part of the Archean. So far as the Vermilion district is concerned, and, indeed, so far as the entire Lake Superior region is concerned, we get no farther back than that period of the primeval ocean in which the Ely greenstone was formed. If there were land areas in this region or elsewhere in the world at an earlier time we have no evidence of it.

After regional volcanic activity continued for an unknown time, it died out, as volcanic activity has elsewhere. Probably this process was a very slow one, although we have no direct evidence upon this point.

Following the Ely greenstone there were orogenic movements and erosion. Correlative with these was the deposition of sediments in the Vermilion district. The mechanical sediments formed at this time are insignificant in amount. The depth of water over the Vermilion district was sufficiently great to make the mechanical sediments entirely subordinate. Here, under quiescent conditions, the iron-bearing carbonate of the Soudan formation was laid down. For much of the district this formation rests directly upon the Ely greenstone, with no intervening mechanical material. The iron-bearing carbonates are chemical or organic sediments, or were more probably formed by a combination of chemical and organic agents.

That life was present in the sea at the time of the deposition of the Soudan formation and furnished organic material to reduce the limonite and carbonate to protoxide is indicated by the graphitic material now associated with these rocks. The iron for the carbonates may have been partly absorbed from the Ely greenstone underlying the formation, but probably was more largely abstracted from the areas of Ely greenstone raised above the water outside the district at present considered. The underground and surface streams would there dissolve the iron salts. They were brought to the Vermilion sea, and there were probably precipitated as limonite and transformed to iron carbonate by processes previously explained.

Following the deposition of the Ely greenstone there was a second great outbreak of igneous activity. At this time various igneous rocks were intruded within the Ely greenstone and the Soudan formation. At this time, or earlier, were the great intrusions of granite represented by the

Archean acid intrusives, the granites of Trout, Basswood, Burntside, and Saganaga lakes and connecting areas. The main masses of these granites are vast batholiths, from which there are innumerable offshoots. These intrusions cut the Ely greenstone most intricately, but all of the granites—for example, the granite of Saganaga Lake—have not been found in such relations to the Soudan formation. It is believed, however, that this age relationship exists and that it is only owing to absence of the Soudan formation in good development near the granite of Saganaga Lake that dikes of the granite have not been found in it. This may, therefore, antedate the Soudan formation and really be of early Archean age, although if this were the case it is thought probable that the disturbances attending its intrusion would have raised the Ely greenstone above the sea at various places in the Vermilion district, and thus would have resulted in the formation of thick mechanical sediments below the Soudan formation. It is therefore thought to be more probable that the granite is contemporaneous with the others, and is later than the Soudan formation.

The Ely greenstone, the mechanical sediments preceding the Soudan jaspers, the Soudan jaspers themselves, and the intrusive rocks following the Soudan constitute the Archean rocks.

Probably contemporaneous with these great intrusions of igneous rock were the powerful orogenic movements following Archean time. These movements probably raised the entire Vermilion district above the sea. They certainly folded the rocks into mountain masses of enormous extent and exceeding complexity, so that the Vermilion district, which up to the present time had been a sea area, was now a land area. No sooner was the district raised above the sea than the epigene forces attacked the land and the process of degradation began. This was very long continued, and land and sea erosion cut deeply into the previous formation. For large parts of the district it removed the entire Soudan formation; in places it cut away the Ely greenstone, exposing the underlying intrusive granite.

Attending the granitic intrusions, the orogenic movements, and the erosion were the metamorphic changes in the rocks. Dependent upon the granite intrusion was the deep-seated alteration of the Ely greenstone, resulting in the production of amphibole-schists and amphibole-gneisses. Adjacent to the granite masses the more superficial agents of metamorphism, and especially those of weathering, greatly changed the carbonate of the

Soudan formation to ferruginous slates and ferruginous cherts, although residual iron carbonate undoubtedly remained.

It therefore appears that the batholithic and dike intrusions of granite, porphyry, etc., and doubtless extrusions, and the orogenic and profound erosion and the metamorphism were contemporary events, or at least largely overlapping. While the intrusive masses are placed in the Archean series, these events chiefly mark the inter-Archean-Huronian time, the most conspicuous evidence of which is the great unconformity between the Archean and the Lower Huronian series. It is clear, however, that Archean time is not sharply separated from inter-Archean-Huronian time, but is connected through the intrusive masses. If there were volcanics contemporaneous with the batholiths of granite and the intrusive masses of porphyry, these were wholly removed by the great period of erosion mentioned below, since no such rocks are found in the district.

After erosion had long continued either the land was reduced to the level of the sea by this process or else subsidence came, or perhaps erosion and subsidence combined to reduce the outer portion of the Vermilion district to the level of the sea. The sea then encroached upon the land. However, the land was uneven, with highlands here and lowlands there, so that the time of the advance of the sea over the district varied considerably. The areas first encroached upon received a thick layer of gravel and bowlders, the material being derived from highlands which had not yet been covered by the sea. Thus there was built up the great Ogishke conglomerate, the lowest formation of the Lower Huronian series. When at last the sea had succeeded in entirely overriding the district, the conditions were no longer favorable for the deposition of coarse mechanical sediments; also it is probable that a certain amount of subsidence further favored quiescent conditions at the bottom of the sea. At this time the Agawa formation was laid down in certain favorable localities, but in small quantity, in the eastern half of the district.

In the western part of the district no chemical or mechanical deposit was found which may be correlated with the Agawa formation in the eastern half of the district. It may be supposed that here the water was not deep enough for such sediments to be produced.

Following the deposition of the rocks of the Agawa formation must have been a long-continued subsidence, for upon the formation was laid down the great thickness of mechanical sediments marked by the Knife Lake slates. These were deposited as muds, grits, and fine gravels. The sea, therefore, must have been one of moderate depth; land areas must have been adjacent, as the formation is so thick that a continual subsidence must have occurred in order that the great mass of material could be piled up. A part of the material was clearly derived from the adjacent land areas; some portion was contributed by contemporaneous volcanoes, for within the Knife Lake slates at various localities are considerable proportions of volcanic ash, showing that volcanic ash was spread far and wide from volcanic centers, and was thus important for upbuilding the Knife Lake slates. The source of this ash has not been discovered. The Ogishke conglomerate, Agawa formation and the Knife Lake slates together constitute the sediments of the Lower Huronian series.

Following the upbuilding of the sediments was another great period of igneous intrusion marked by the Giants Range granite, the Snowbank granite, and the Cacaquabic granite. While the acid intrusives mentioned were the dominant ones, there are certain more or less schistose basic and intermediate intrusives occurring in isolated dikes in the various rocks thus far described which belong to this same general period of igneous activity. The Snowbank granite and granites of equivalent age, etc., are placed with the Lower Huronian series, although they more probably belong with the great geologic revolution following the comparatively quiescent conditions of Lower Huronian sedimentation, and contemporaneous with lavas probably formed at the surface. If such lavas were laid down they were apparently wholly removed by the deep-seated erosion mentioned below.

This revolution was caused by the orogenic movements which now followed. These were of the most severe kind, and continued long. As a result the Lower Huronian series were thrown into a set of close east-west folds and steeper cross folds. This folding must have produced great mountain masses. No sooner did the orogenic movements raise the land above the sea than the epigene forces again began their work of hewing it down. The period of erosion was very long, so long in fact that in various places the entire Lower Huronian series was cut through, laying bare the Archean. Contemporaneous with and largely caused by the folding and partly by the intrusion of the igneous rocks and by the erosion was a second great period of metamorphism. The great mass of muds of the

Lower Huronian series became transformed to slates. The sediments near the Giants Range and Snowbank granites were transformed to schists and gneisses. From the iron carbonates of the Agawa formation ferruginous slates and ferruginous cherts were formed, although this process by no means neared completion. It appears that following Lower Huronian time, as in inter-Archean-Huronian time, igneous intrusions, orogenic movements, erosion, and metamorphism were largely contemporary, or at least overlapping, and that they were largely the result of the same causes; that is to say, there was a time of the readjustment of the earth's crust where before there had been a time of sedimentation. These earth movements resulted in folding and in vulcanism, and consequent upon this were erosion, and dependent upon all this was metamorphism, both deep seated and surface.

Following the unconformity above Lower Huronian time the Vermilion district was again depressed and the Upper Huronian (Animikie) series was deposited above the upturned rocks of Archean and Lower Huronian age. Only a small area in the eastern part of the Vermilion district is covered by the Upper Huronian sediments, and we have little data in this district for determining the history of this time. The basal formation of the Upper Huronian in the Vermilion district is the Gunflint formation, whose character is such as to indicate that it was deposited in relatively deep water or a protected area of the sea. Southwest of the Vermilion district in the Mesabi district a conglomerate occurs at the base of the Upper Huronian below the Biwabik formation which is correlative with the Gunflint formation of the Vermilion district. We thus conclude that while the Upper Huronian sea advanced, conglomerates were formed to the west, but that in the Vermilion district the conditions were not favorable for the production of this kind of rock. Over the Gunflint formation was then deposited possibly 10,000 and more feet of Rove slates and graywackes. These rocks presumably covered the entire Vermilion district and probably extended far northward beyond the district, but all evidence of such extension has been removed by erosion.

Following the period of deposition of the Upper Huronian there came an upheaval succeeded by a long period of extensive erosion. This erosion removed great thicknesses of the overlying Upper Huronian rocks and in some cases the entire thickness, and having cut through the Upper

Huronian even cut down into the Lower Huronian and Archean rocks. From evidence in other districts of the Lake Superior region, but not from evidence in the Vermilion district, the unconformity represented by this period of erosion is known to have been important.

Following the Upper Huronian unconformity came the lava flows of the Keweenawan. These probably accumulated to immense thickness upon the beveled edges of the Upper Huronian series. There is no evidence that these flows were not subaërial—that is, deposited upon the Upper and Lower Huronian and Archean series while they were still land areas. How far the process of upbuilding of the Keweenawan had continued before the next great event it is impossible to say, but it is probable that thousands of feet of lavas were erupted, and that sandstones and conglomerates were deposited in the upper parts of the series between these lavas. If this be the case, the land must have again subsided below the sea. However this may be, after a very considerable thickness of Keweenawan lava had accumulated, there came the great laccolithic intrusion of Duluth gabbro, which now has a surface area of nearly 200 square miles and extends from Duluth eastward beyond the eastern end of the Vermilion district, and which bounds the Vermilion district on the south from the Kawishiwi River eastward. The planes between the various formations would be the natural planes of easiest resistance which an intrusive would follow, and these planes the Keweenawan gabbro seems to have followed for the most part. In the western and central portion of the district the gabbro, to judge from the way in which it overlaps on the Archean and Lower Huronian rocks, and from the fact that it has included in it at various places along its northern edge masses of the Gunflint formation of varying size, seems to have followed along the plane between the Upper Huronian and the Archean and Lower Huronian. In the east the gabbro laccolith began to rise and there beveled the edges of the Upper Huronian, and at one place is even found intrusive in the Keweenawan lava flows. It is believed that the numerous sills, named Logan sills by Lawson, which are so abundantly found in the Animikie, are but part of the same magma from which the gabbro came and that they were introduced at the same time. Finally the great diabase dikes of Beaver Bay and other places along the Minnesota coast, which intruded the Keweenawan lavas, are probably connected with this great gabbro laccolith.

It is not supposed that the intrusion of this enormous mass of lava, probably the greatest known laccolith, occurred within a brief time. It has been noted that this laccolith is 150 miles long and probably thousands of feet in thickness—how thick is entirely unknown. The intrusion of so vast a mass of material must have occupied a very great length of time. The parts earlier intruded were doubtless solidified long before magma ceased to enter. Thus these latter parts would be found as dikes in the earlier solidified parts. There would be great variation in its coarseness of crystallization. There would be ample time for the various processes of differentiation by fractional crystallization and separation by gravity and other processes, and thus is explained the structural complexity of the gabbro and its great variation in mineral and chemical character. Perhaps contemporary with the intrusion of the gabbro, perhaps later than it, perhaps in part both, was the gentle tilting of the Keweenawan lavas, the Duluth gabbro, and the Animikie, all together, to the south, under Lake Superior, and the much more pronounced northwest tilting toward the same lake of the Penokee series south of Lake Superior. To this tilting in opposite directions on opposite sides of the lake is due the Lake Superior Basin.

It is believed that at the time of the formation of the Lake Superior syncline the Giants range anticlinal area was correspondingly upheaved, and that thus the present Giants range was actually created by this movement, although, as has been stated in the previous pages, the location of the range was actually determined possibly as early as the folding following the Archean when the protaxis of the range is thought to have been first formed. Since this earliest time repeated movements of elevation, particularly the one at the close of Lower Huronian time, succeeded by subsidence and erosion, have followed along this old line of weakness. The actual present condition of the range in its minor features is of course due to the erosion and then glacial deposition which have occured subsequent to Keweenawan time and which are briefly outlined in the following pages.

Contemporaneous with and following the intrusion of the Keweenawan gabbro is the peculiar metamorphism which marks the rocks of the Lower Huronian, Upper Huronian, and Archean along its border. It has been noted that the Gunflint formation adjacent to it was changed to a banded granitic textured rock, consisting of iron silicates, magnetite, and quartz.

These iron silicates comprise chrysolites, pyroxenes, and amphiboles. They are very coarse grained and they stand as the extreme of deep-seated static metamorphism of an iron-bearing carbonate. The muds and grits of the Knife Lake formation and the conglomerates of the Ogishke formation adjacent to the gabbro were completely crystallized largely into granitic-textured rocks described (pp. 315, 342). These are the best representatives of the production of granitic textured rocks from heterogeneous mechanical sediments known to the writer. They were produced under deep-seated static conditions where high temperature prevailed.

All of the complex events thus far described preceded Cambrian time. This history is Archean and Algonkian. In another place it has been shown by Walcott[a] that the Cambrian transgression over the North American continent began at the southeast and extended to the northwest, and that it continued through Lower and Middle Cambrian time before the sediments were deposited in the Lake Superior region. This great erosion period was probably partly contemporaneous with the tilting which produced the Lake Superior syncline. The erosion of this time laid bare the great laccolith of gabbro, as well as the beds of the overlying lavas, and thus exposed to light of day all of the great series of rocks—within the Vermilion district itself the Archean, the Lower Huronian, and the Upper Huronian series; south of these the great batholith of gabbro; and south of this the Keweenawan lavas. Finally, however, the sea overrode this region, and the Cambrian sandstone was laid down in the Lake Superior Basin and along its border. Remnants of it have been found far inland, but none in the Vermilion district itself. However, it can not be doubted that over the Vermilion district were deposited Cambrian or Silurian rocks, and therefore the Paleozoic was there represented.

The next great step in the history of the region was the elevation of the land above the sea and long-continued denudation. This period of denudation has generally been known as the Cretaceous period of base-leveling. Whether the sea actually overrode the Vermilion district and there deposited the Cretaceous rocks is uncertain. However, it is certain that the Cretaceous sea reached within a comparatively short distance of the district, for outliers of the Cretaceous rocks are now known within 20

[a] Correlation Papers: Cambrian, by C. D. Walcott: Bull. U. S. Geol. Survey No. 81, 1891, p. 364.

miles southwest of Vermilion Lake, and it seems highly probable that Cretaceous rocks were laid over the district. However, in this case the long-continued erosion of Cretaceous time had probably removed all of the Paleozoic sediments, and had reduced the land to a rough peneplain before the deposition of the Upper Cretaceous rocks.

It can not be said that this period of base-leveling in the Vermilion district was nearly so complete as in central Wisconsin. However, the hills rise to approximately the same altitude. If one ascends to some high point he finds an approximate horizon line above which only a few points project, as, for instance, the Sawtooth range.

Following the period of Cretaceous base-leveling the land was raised approximately to its present altitude, and a second cycle of erosion was inaugurated. This cycle has continued to the present time. In the early part of this long cycle river erosion was the important factor, and at this time were scooped out the longitudinal valleys following the softer rocks and the various structures of the rocks. The drainage was adjusted to the character of the rocks. The slate areas were largely valleys; the more resistant areas were largely highlands. Finally, there came the various ice advances, at which time the valleys were widened and deepened, the hills were rounded, and glacial débris was dropped here and there, but especially in the valleys. When the ice last receded the present topography was substantially shaped. The depressions filled with water until they overran their rims at the lowest points, thus forming the lakes. The lakes were thus connected by streams, and the present irregular drainage (discussed on pp. 39–46) was inaugurated. Thus we have explained the present topography of the district.

In conclusion, we see that the Vermilion district presents one of the longest geologic histories of any region in the world. Apparently the Ely greenstone, the most ancient formation, was laid down in primeval time and the Soudan formation was deposited above it. Since that time there were five great periods of deposition: The Lower Huronian, the Upper Huronian, the Keweenawan, the Paleozoic, and the Cretaceous.

There were four great periods of igneous activity: The Ely greenstone, the great batholithic intrusions at the end of Archean time, the hardly less important batholithic intrusions at the end of Lower Huronian time, and the great Keweenawan period of volcanic extrusion and intrusion. There was also possibly contemporary volcanic activity at the time of the Knife Lake slates.

Finally, there were four great periods of orogenic movements, denudation, and metamorphism: Following the Archean series; following the Lower Huronian; following the Upper Huronian; and following the Keweenawan.

Also there were three other great periods of denudation: The Cambrian and the Cretaceous periods of base-leveling, and finally the period following the Cretaceous, extending to the present time.

INDEX.

C.

S.

O

PUBLICATIONS OF UNITED STATES GEOLOGICAL SURVEY.

[Monograph XLV.]

The serial publications of the United States Geological Survey consist of (1) Annual Reports, (2) Monographs, (3) Professional Papers, (4) Bulletins, (5) Mineral Resources, (6) Water-Supply and Irrigation Papers, (7) Topographic Atlas of the United States—folios and separate sheets thereof, (8) Geologic Atlas of the United States—folios thereof. The classes numbered 2, 7, and 8 are sold at cost of publication; the others are distributed free. A circular giving complete lists may be had on application.

MONOGRAPHS.

I. Lake Bonneville, by G. K. Gilbert. 1890. 4°. xx, 438 pp. 51 pl. 1 map. Price $1.50.

II. Tertiary history of the Grand Cañon district, with atlas, by C. E. Dutton, Capt., U. S. A. 1882. 4°. xiv, 264 pp. 42 pl. and atlas of 24 sheets folio. Price $10.

III. Geology of the Comstock lode and the Washoe district, with atlas, by G. F. Becker. 1882. 4°. xv, 422 pp. 7 pl. and atlas of 21 sheets folio. Price $11.

IV. Comstock mining and miners, by Eliot Lord. 1883. 4°. xiv, 451 pp. 3 pl. Price $1.50.

V. The copper-bearing rocks of Lake Superior, by R. D. Irving. 1883. 4°. xvi, 464 pp. 15 l. 29 pl. and maps. Price $1.85.

VI. Contributions to the knowledge of the older Mesozoic flora of Virginia, by W. M. Fontaine. 1883. 4°. xi, 144 pp. 54 l. 54 pl. Price $1.05.

VII. Silver-lead deposits of Eureka, Nevada, by J. S. Curtis. 1884. 4°. xiii, 200 pp. 16 pl. Price $1.20.

VIII. Paleontology of the Eureka district, by C. D. Walcott. 1884. 4°. xiii, 298 pp. 24 l. 24 pl. Price $1.10.

IX. Brachiopoda and Lamellibranchiata of the Raritan clays and greensand marls of New Jersey, by R. P. Whitfield. 1885. 4°. xx, 338 pp. 35 pl. 1 map. Price $1.15.

X. Dinocerata. A monograph of an extinct order of gigantic mammals, by O. C. Marsh. 1886. 4°. xviii, 243 pp. 56 l. 56 pl. Price $2.70.

XI. Geological history of Lake Lahontan, a Quaternary lake of northwestern Nevada, by I. C. Russell. 1885. 4°. xiv, 288 pp. 46 pl. and maps. Price $1.75.

XII. Geology and mining industry of Leadville, Colorado, with atlas, by S. F. Emmons. 1886. 4°. xxix, 770 pp. 45 pl. and atlas of 35 sheets folio. Price $8.40.

XIII. Geology of the quicksilver deposits of the Pacific slope, with atlas, by G. F. Becker. 1888. 4°. xix, 486 pp. 7 pl. and atlas of 14 sheets folio. Price $2.

XIV. Fossil fishes and fossil plants of the Triassic rocks of New Jersey and the Connecticut Valley, by J. S. Newberry. 1888. 4°. xiv, 152 pp. 26 pl. Price $1.

XV. The Potomac or younger Mesozoic flora, by W. M. Fontaine. 1889. 4°. xiv, 377 pp. 180 pl. Text and plates bound separately. Price $2.50.

XVI. The Paleozoic fishes of North America, by J. S. Newberry. 1889. 4°. 340 pp. 53 pl. Price $1.00.

XVII. The flora of the Dakota group, a posthumous work, by Leo Lesquereux. Edited by F. H. Knowlton. 1891. 4°. 400 pp. 66 pl. Price $1.10.

XVIII. Gasteropoda and Cephalopoda of the Raritan clays and greensand marls of New Jersey, by R. P. Whitfield. 1891. 4°. 402 pp. 50 pl. Price $1.

XIX. The Penokee iron-bearing series of northern Wisconsin and Michigan, by R. D. Irving and C. R. Van Hise. 1892. 4°. xix, 534 pp. Price $1.70.

XX. Geology of the Eureka district, Nevada, with an atlas, by Arnold Hague. 1892. 4°. xvii, 419 pp. 8 pl. Price $5.25.

XXI. The Tertiary rhynchophorous Coleoptera of the United States, by S. H. Scudder. 1893. 4°. xi, 206 pp. 12 pl. Price 90 cents.

XXII. A manual of topographic methods, by Henry Gannett, chief topographer. 1893. 4°. xiv, 300 pp. 18 pl. Price $1.

XXIII. Geology of the Green Mountains in Massachusetts, by Raphael Pumpelly, T. N. Dale, and J. E. Wolff. 1894. 4°. xiv, 206 pp. 23 pl. Price $1.30.

XXIV. Mollusca and Crustacea of the Miocene formations of New Jersey, by R. P. Whitfield. 1894. 4°. 193 pp. 24 pl. Price 90 cents.
XXV. The Glacial Lake Agassiz, by Warren Upham. 1895. 4°. xxiv, 658 pp. 38 pl. Price $1.70.
XXVI. Flora of the Amboy clays, by J. S. Newberry; a posthumous work, edited by Arthur Hollick. 1895. 4°. 260 pp. 58 pl. Price $1.
XXVII. Geology of the Denver Basin in Colorado, by S. F. Emmons, Whitman Cross, and G. H. Eldridge. 1896. 4°. 556 pp. 31 pl. Price $1.50.
XXVIII. The Marquette iron-bearing district of Michigan, with atlas, by C. R. Van Hise and W. S. Bayley, including a chapter on the Republic trough, by H. L. Smyth. 1895. 4°. 608 pp. 35 pl. and atlas of 39 sheets folio. Price $5.75.
XXIX. Geology of old Hampshire County, Massachusetts, comprising Franklin, Hampshire, and Hampden counties, by B. K. Emerson. 1898. 4°. xxi, 790 pp. 35 pl. Price $1.90.
XXX. Fossil Medusæ, by C. D. Walcott. 1898. 4°. ix, 201 pp. 47 pl. Price $1.50.
XXXI. Geology of the Aspen mining district, Colorado, with atlas, by J. E. Spurr. 1898. 4°. xxxv, 260 pp. 43 pl. and atlas of 30 sheets folio. Price $3.60.
XXXII. Geology of the Yellowstone National Park, Part II, descriptive geology, petrography, and paleontology, by Arnold Hague, J. P. Iddings, W. H. Weed, C. D. Walcott, G. H. Girty, T. W. Stanton, and F. H. Knowlton. 1899. 4°. xvii, 893 pp. 121 pl. Price $2.45.
XXXIII. Geology of the Narragansett Basin, by N. S. Shaler, J. B. Woodworth, and A. F. Foerste. 1899. 4°. xx, 402 pp. 31 pl. Price $1.
XXXIV. The glacial gravels of Maine and their associated deposits, by G. H. Stone. 1899. 4°. xiii, 499 pp. 52 pl. Price $1.30.
XXXV. The later extinct floras of North America, by J. S. Newberry; edited by Arthur Hollick. 1898. 4°. xviii, 295 pp. 68 pl. Price $1.25.
XXXVI. The Crystal Falls iron-bearing district of Michigan, by J. M. Clements and H. L. Smyth; with a chapter on the Sturgeon River tongue, by W. S. Bayley, and an introduction by C. R. Van Hise. 1899. 4°. xxxvi, 512 pp. 53 pl. Price $2.
XXXVII. Fossil flora of the Lower Coal Measures of Missouri, by David White. 1899. 4°. xi, 467 pp. 73 pl. Price $1.25.
XXXVIII. The Illinois glacial lobe, by Frank Leverett. 1899. 4°. xxi, 817 pp. 24 pl. Price $1.60.
XXXIX. The Eocene and Lower Oligocene coral faunas of the United States, with descriptions of a few doubtfully Cretaceous species, by T. W. Vaughan. 1900. 4°. 263 pp. 24 pl. Price $1.10.
XL. Adephagous and clavicorn Coleoptera from the Tertiary deposits at Florissant, Colorado, with descriptions of a few other forms and a systematic list of the non-rhyncophorous Tertiary Coleoptera of North America, by S. H. Scudder. 1900. 4°. 148 pp. 11 pls. Price 80 cents.
XLI. Glacial formations and drainage features of the Erie and Ohio basins, by Frank Leverett. 1902. 4°. 802 pp. 26 pls. Price $1.75.
XLII. Carboniferous ammonoids of America, by J. P. Smith. 1903. 4°. 211 pp. 29 pls. Price 85 cents.
XLIII. The Mesabi iron-bearing district of Minnesota, by C. K. Leith. 1903. 4°. 316 pp. 33 pls. Price $1.50.
XLIV. Pseudoceratites of the Cretaceous, by Alpheus Hyatt, edited by T. W. Stanton. 1903. 4°. 350 pp. 47 pls. Price ——.
XLV. The Vermilion iron-bearing district of Minnesota, with atlas, by J. M. Clements. 1903. 4°. 463 pp. 13 pls. Price ——.

All remittances must be by MONEY ORDER, made payable to the Director of the United States Geological Survey, or in CURRENCY—the exact amount. Checks, drafts, and postage stamps can not be accepted. Correspondence should be addressed to

The DIRECTOR,
UNITED STATES GEOLOGICAL SURVEY,
WASHINGTON, D. C.

LIBRARY CATALOGUE SLIPS.

[Mount each slip upon a separate card, placing the subject at the top of the second slip. The name of the series should not be repeated on the series card, but add the additional numbers, as received, to the first entry.]

Author.

Clements, J[ulius] Morgan.

. . . The Vermilion iron-bearing district of Minnesota, with an atlas; by J. Morgan Clements. Charles Richard Van Hise, geologist in charge. Washington, Gov't print. off., 1903.

(U. S. Geological survey. Monographs v. xlv.) 463 p. 13 pl. 30cm. and atlas (26 sheets) 53x46cm.

Subject.

Clements, J[ulius] Morgan.

. . . The Vermilion iron-bearing district of Minnesota, with an atlas; by J. Morgan Clements. Charles Richard Van Hise, geologist in charge. Washington, Gov't print. off., 1903.

(U. S. Geological survey. Monographs v. xlv.) 463 p. 13 pl. 30cm. and atlas (26 sheets) 53x46cm.

Series.

U. S. Geological survey.

Monographs.

v. 45. Clements, J. M. The Vermilion iron-bearing district of Minnesota, with an atlas. 1903.

Reference.

U. S. Dept. of the Interior.

see also

U. S. Geological survey.